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REVIEW OF PARTICLE PHYSICS*

Particle Data Group

Abstract

This biennial *Review* summarizes much of Particle Physics. Using data from previous editions, plus 1600 new measurements from 550 papers, we list, evaluate, and average measured properties of gauge bosons, leptons, quarks, mesons, and baryons. We also summarize searches for hypothetical particles such as Higgs bosons, heavy neutrinos, and supersymmetric particles. All the particle properties and search limits are listed in Summary Tables. We also give numerous tables, figures, formulae, and reviews of topics such as the Standard Model, particle detectors, probability, and statistics. A booklet is available containing the Summary Tables and abbreviated versions of some of the other sections of this full *Review*. All tables, listings, and reviews (and errata) are also available on the Particle Data Group website: `http://pdg.lbl.gov`.

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INTRODUCTION

ONLINE PARTICLE PHYSICS INFORMATION

INTRODUCTION

1. Overview

The *Review of Particle Physics* and the abbreviated version, the *Particle Physics Booklet,* are reviews of the field of Particle Physics. This complete *Review* includes a compilation/evaluation of data on particle properties, called the "Particle Listings." These Listings include 1900 new measurements from 700 papers, in addition to the 14,000 measurements from 4000 papers that first appeared in previous editions.

Both books include Summary Tables with our best values and limits for particle properties such as masses, widths or lifetimes, and branching fractions, as well as an extensive summary of searches for hypothetical particles. In addition, we give a long section of "Reviews, Tables, and Plots" on a wide variety of theoretical and experimental topics, a quick reference for the practicing particle physicist.

The *Review* and the *Booklet* are published in even-numbered years. This edition is an updating through December 1995 (and, in some areas, well into 1996). As described in the section "Using Particle Physics Databases" following this introduction, the content of this *Review* is available on the World-Wide Web, and is updated between printed editions (`http://pdg.lbl.gov/`).

The Summary Tables give our best values of the properties of the particles we consider to be well established, a summary of search limits for hypothetical particles, and a summary of experimental tests of conservation laws.

The Particle Listings contain all the data used to get the values given in the Summary Tables. Other measurements considered recent enough or important enough to mention, but which for one reason or another are not used to get the best values, appear separately just beneath the data we do use for the Summary Tables. The Particle Listings also give information on unconfirmed particles and on particle searches, as well as short "reviews" on subjects of particular interest or controversy.

The Particle Listings were once an archive of all published data on particle properties. This is no longer possible because of the large quantity of data. We refer interested readers to earlier editions for data now considered to be obsolete.

We organize the particles into six categories:

- Gauge and Higgs bosons
- Leptons
- Quarks
- Mesons
- Baryons
- Searches for monopoles, supersymmetry, compositeness, *etc.*

The last category only includes searches for particles that do not belong to the previous groups; searches for heavy charged leptons and massive neutrinos, by contrast, are with the leptons.

In Sec. 2 of this Introduction, we list the main areas of responsibility of the authors, and also list our large number of consultants, without whom we would not have been able to produce this *Review.* In Sec. 3, we mention briefly the naming scheme for hadrons. In Sec. 4, we discuss our procedures for choosing among measurements of particle properties and for obtaining best values of the properties from the measurements.

The accuracy and usefulness of this *Review* depend in large part on interaction between its users and the authors. We appreciate comments, criticisms, and suggestions for improvements of any kind. Please send them to the appropriate author, according to the list of responsibilities in Sec. 2 below, or to the LBNL addresses below.

To order a copy of the *Review* or the *Particle Physics Booklet* from North and South America, Australia, and the Far East, write to

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Graviton	D.E. Groom*
W, Z	C. Caso,* A. Gurtu*
Higgs bosons	K. Hikasa, M.L. Mangano*
Heavy bosons	C.D. Carone, M. Tanabashi, T.G. Trippe*
Axions	M.L. Mangano,* H. Murayama, K.A. Olive

Leptons

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ν_τ, τ	D.E. Groom,* K.G. Hayes, K. Mönig*

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Free quark	D.E. Groom*

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Baryons

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Unstable baryons	C.G. Wohl*, R.L. Workman
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Bottom baryons	T.G. Trippe, W.-M. Yao*

Miscellaneous searches

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The Particle Data Group benefits greatly from the assistance of some 700 physicists who are asked to verify every piece of data entered into this *Review*. Of special value is the advice of the PDG Advisory Committee which meets annually and thoroughly reviews all aspects of our operation. The members of the 1996 committee were:

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3. Naming scheme for hadrons

We introduced in the 1986 edition [2] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of u, d, and s quarks. Otherwise, the only important change to known hadrons was that the $F^{\pm}$ became the $D_s^{\pm}$. None of the lightest pseudoscalar or vector mesons changed names, nor did the $c\bar{c}$ or $b\bar{b}$ mesons (we do, however, now use χ_c for the $c\bar{c}$ χ states), nor did any of the established baryons. The Summary Tables give both the new and old names whenever a change has occurred.

The scheme is described in "Naming Scheme for Hadrons" (p. 80) of this *Review*.

We give here our conventions on type-setting style. Particle symbols are italic (or slanted) characters: e^-, p, Λ, π^0, K_L, D_s^+, b. Charge is indicated by a superscript: B^-, Δ^{++}. Charge is not normally indicated for p, n, or the quarks, and is optional for neutral isosinglets: η or η^0. Antiparticles and particles are distinguished by charge for charged leptons and mesons: τ^+, K^-. Otherwise, distinct antiparticles are indicated by a bar (overline): $\overline{\nu}_\mu$, $\overline{t}$, $\overline{p}$, $\overline{K}^0$, and $\overline{\Sigma}^+$ (the antiparticle of the Σ^-).

4. Procedures

4.1. ***Selection and treatment of data***: The Particle Listings contain all relevant data known to us that are published in journals. With very few exceptions, we do not include results from preprints or conference reports. Nor do we include data that are of historical importance only (the Listings are not an archival record). We search every volume of 20 journals through our cutoff date for relevant data. We also include later published papers that are sent to us by the authors (or others).

In the Particle Listings, we clearly separate measurements that are used to calculate or estimate values given in the Summary Tables from measurements that are not used. We give explanatory comments in many such cases. Among the reasons a measurement might be excluded are the following:

- It is superseded by or included in later results.
- No error is given.
- It involves assumptions we question.
- It has a poor signal-to-noise ratio, low statistical significance, or is otherwise of poorer quality than other data available.
- It is clearly inconsistent with other results that appear to be more reliable. Usually we then state the criterion, which sometimes is quite subjective, for selecting "more reliable" data for averaging. See Sec. 4.
- It is not independent of other results.
- It is not the best limit (see below).
- It is quoted from a preprint or a conference report.

In some cases, *none* of the measurements is entirely reliable and no average is calculated. For example, the masses of many of the baryon resonances, obtained from partial-wave analyses, are quoted as estimated ranges thought to probably include the true values, rather than as averages with errors. This is discussed in the Baryon Particle Listings.

For upper limits, we normally quote in the Summary Tables the strongest limit. We do not average or combine upper limits except in a very few cases where they may be re-expressed as measured numbers with Gaussian errors.

As is customary, we assume that particle and antiparticle share the same spin, mass, and mean life. The Tests of Conservation Laws table, following the Summary Tables, lists tests of *CPT* as well as other conservation laws.

We use the following indicators in the Particle Listings to tell how we get values from the tabulated measurements:

- OUR AVERAGE—From a weighted average of selected data.
- OUR FIT—From a constrained or overdetermined multi-parameter fit of selected data.
- OUR EVALUATION—Not from a direct measurement, but evaluated from measurements of related quantities.
- OUR ESTIMATE—Based on the observed range of the data. Not from a formal statistical procedure.
- OUR LIMIT—For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

An experimentalist who sees indications of a particle will of course want to know what has been seen in that region in the past. Hence we include in the Particle Listings all reported states that, in our opinion, have sufficient statistical merit and that have not been disproved by more reliable data. However, we promote to the Summary Tables only those states that we feel are well established. This judgment is, of course, somewhat subjective and no precise criteria can be given. For more detailed discussions, see the minireviews in the Particle Listings.

4.2. ***Averages and fits*:** We divide this discussion on obtaining averages and errors into three sections: (1) treatment of errors; (2) unconstrained averaging; (3) constrained fits.

4.2.1. *Treatment of errors:* In what follows, the "error" δx means that the range $x \pm \delta x$ is intended to be a 68.3% confidence interval about the central value x. We treat this error as if it were Gaussian. Thus when the error *is* Gaussian, δx is the usual one standard deviation (1σ). Many experimenters now give statistical and systematic errors separately, in which case we usually quote both errors, with the statistical error first. For averages and fits, we then add the the two errors in quadrature and use this combined error for δx.

When experimenters quote asymmetric errors $(\delta x)^+$ and $(\delta x)^-$ for a measurement x, the error that we use for that measurement in making an average or a fit with other measurements is a continuous function of these three quantities. When the resultant average or fit $\overline{x}$ is less than $x-(\delta x)^-$, we use $(\delta x)^-$; when it is greater than $x+(\delta x)^+$, we use $(\delta x)^+$. In between, the error we use is a linear function of x. Since the errors we use are functions of the result, we iterate to get the final result. Asymmetric output errors are determined from the input errors assuming a linear relation between the input and output quantities.

In fitting or averaging, we usually do not include correlations between different measurements, but we try to select data in such a way as to reduce correlations. Correlated errors are, however, treated explicitly when there are a number of results of the form $A_i \pm \sigma_i \pm \Delta$ that have identical systematic errors Δ. In this case, one can first average the $A_i \pm \sigma_i$ and then combine the resulting statistical error with Δ. One obtains, however, the same result by averaging $A_i \pm (\sigma_i^2 + \Delta_i^2)^{1/2}$, where $\Delta_i = \sigma_i \Delta [\sum (1/\sigma_j^2)]^{1/2}$. This procedure has the advantage that, with the modified systematic errors Δ_i, each measurement may be treated as independent and averaged in the usual way with other data. Therefore, when appropriate, we adopt this procedure. We tabulate Δ and invoke an automated procedure that computes Δ_i before averaging and we include a note saying that there are common systematic errors.

Another common case of correlated errors occurs when experimenters measure two quantities and then quote the two and their difference, *e.g.*, m_1, m_2, and $\Delta = m_2 - m_1$. We cannot enter all of m_1, m_2 and Δ into a constrained fit because they are not independent. In some cases, it is a good approximation to ignore the quantity with the largest error and put the other two into the fit. However, in some cases correlations are such that the errors on m_1, m_2 and Δ are comparable and none of the three values can be ignored. In this case, we put all three values into the fit and invoke an automated procedure to increase the errors prior to fitting such that the three quantities can be treated as independent measurements in the constrained fit. We include a note saying that this has been done.

4.2.2. *Unconstrained averaging:* To average data, we use a standard weighted least-squares procedure and in some cases, discussed below, increase the errors with a "scale factor." We begin by assuming that measurements of a given quantity are uncorrelated, and calculate a weighted average and error as

$$\overline{x} \pm \delta\overline{x} = \frac{\sum_i w_i\, x_i}{\sum_i w_i} \pm \left(\sum_i w_i\right)^{-1/2} , \qquad (1)$$

where

$$w_i = 1/(\delta x_i)^2 .$$

Here x_i and δx_i are the value and error reported by the ith experiment, and the sums run over the N experiments. We then calculate $\chi^2 = \sum w_i(\overline{x} - x_i)^2$ and compare it with $N-1$, which is the expectation value of χ^2 if the measurements are from a Gaussian distribution.

If $\chi^2/(N-1)$ is less than or equal to 1, and there are no known problems with the data, we accept the results.

If $\chi^2/(N-1)$ is very large, we may choose not to use the average at all. Alternatively, we may quote the calculated average, but then make an educated guess of the error, a conservative estimate designed to take into account known problems with the data.

Finally, if $\chi^2/(N-1)$ is greater than 1, but not greatly so, we still average the data, but then also do the following:

(a) We increase our quoted error, $\delta\overline{x}$ in Eq. (1), by a scale factor S defined as

$$S = \left[\chi^2/(N-1)\right]^{1/2} . \qquad (2)$$

Our reasoning is as follows. The large value of the χ^2 is likely to be due to underestimation of errors in at least one of the experiments. Not knowing which of the errors are underestimated, we assume they are all underestimated by the same factor S. If we scale up all the input errors by this factor, the χ^2 becomes $N-1$, and of course the output error $\delta\overline{x}$ scales up by the same factor. See Ref. 3.

When combining data with widely varying errors, we modify this procedure slightly. We evaluate S using only the experiments with smaller errors. Our cutoff or ceiling on δx_i is arbitrarily chosen to be

$$\delta_0 = 3N^{1/2}\,\delta\overline{x}\,,$$

where $\delta\overline{x}$ is the unscaled error of the mean of all the experiments. Our reasoning is that although the low-precision experiments have little influence on the values $\overline{x}$ and $\delta\overline{x}$, they can make significant contributions to the χ^2, and the contribution of the high-precision experiments thus tends to be obscured. Note that if each experiment has the same error δx_i, then $\delta\overline{x}$ is $\delta x_i/N^{1/2}$, so each δx_i is well below the cutoff. (More often, however, we simply exclude measurements with relatively large errors from averages and fits: new, precise data chase out old, imprecise data.)

Our scaling procedure has the property that if there are two values with comparable errors separated by much more than their stated errors (with or without a number of other values of lower accuracy), the scaled-up error $\delta\overline{x}$ is approximately half the interval between the two discrepant values.

We emphasize that our scaling procedure for *errors* in no way affects central values. And if you wish to recover the unscaled error $\delta\overline{x}$, simply divide the quoted error by S.

(b) If the number M of experiments with an error smaller than δ_0 is at least three, and if $\chi^2/(M-1)$ is greater than 1.25, we show in the Particle Listings an ideogram of the data. Figure 1 is an example. Sometimes one or two data points lie apart from the main body; other times the data split into two or more groups. We extract no numbers from these ideograms; they are simply visual aids, which the reader may use as he or she sees fit.

Each measurement in an ideogram is represented by a Gaussian with a central value x_i, error δx_i, and area proportional to $1/\delta x_i$. The choice of $1/\delta x_i$ for the area is somewhat arbitrary. With this choice, the center of gravity of the ideogram corresponds to an average that uses weights $1/\delta x_i$ rather than the $(1/\delta x_i)^2$ actually used in the averages. This may be appropriate when some of the experiments have seriously underestimated systematic errors. However, since for this choice of area the height of the Gaussian for each measurement is proportional to $(1/\delta x_i)^2$, the peak position of the ideogram will often favor the high-precision measurements at least as much as does the least-squares average. See our 1986 edition [2] for a detailed discussion of the use of ideograms.

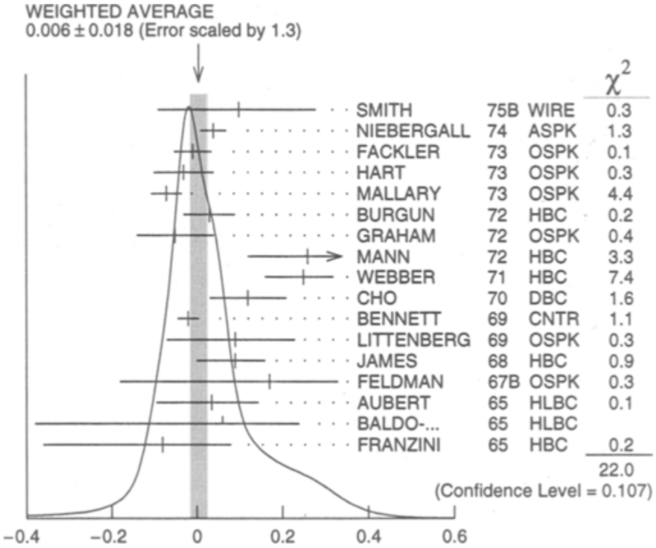

Figure 1: A typical ideogram. The arrow at the top shows the position of the weighted average, while the width of the shaded pattern shows the error in the average after scaling by the factor S. The column on the right gives the χ^2 contribution of each of the experiments. Note that the next-to-last experiment, denoted by the incomplete error flag ($\perp$), is not used in the calculation of S (see the text).

4.2.3. *Constrained fits:* Except for trivial cases, all branching ratios and rate measurements are analyzed by making a simultaneous least-squares fit to all the data and extracting the partial decay fractions P_i, the partial widths Γ_i, the full width Γ (or mean life), and the associated error matrix.

Assume, for example, that a state has m partial decay fractions P_i, where $\sum P_i = 1$. These have been measured in N_r different ratios R_r, where, e.g., $R_1 = P_1/P_2$, $R_2 = P_1/P_3$, *etc.* [We can handle any ratio R of the form $\sum \alpha_i P_i / \sum \beta_i P_i$, where α_i and β_i are constants, usually 1 or 0. The forms $R = P_iP_j$ and $R = (P_iP_j)^{1/2}$ are also allowed.] Further assume that *each* ratio R has been measured by N_k experiments (we designate each experiment with a subscript k, e.g., R_{1k}). We then find the best values of the fractions P_i by minimizing the χ^2 as a function of the $m-1$ independent parameters:

$$\chi^2 = \sum_{r=1}^{N_r} \sum_{k=1}^{N_k} \left(\frac{R_{rk} - R_r}{\delta R_{rk}} \right)^2 , \tag{3}$$

where the R_{rk} are the measured values and R_r are the fitted values of the branching ratios.

In addition to the fitted values $\overline{P}_i$, we calculate an error matrix $\langle \delta\overline{P}_i \; \delta\overline{P}_j \rangle$. We tabulate the diagonal elements of $\delta\overline{P}_i = \langle \delta\overline{P}_i \; \delta\overline{P}_i \rangle^{1/2}$ (except that some errors are scaled as discussed below). In the Particle Listings, we give the complete correlation matrix; we also calculate the fitted value of each ratio, for comparison with the input data, and list it above the relevant input, along with a simple unconstrained average of the same input.

Three comments on the example above:

(1) There was no connection assumed between measurements of the full width and the branching ratios. But

often we also have information on partial widths Γ_i as well as the total width Γ. In this case we must introduce Γ as a parameter in the fit, along with the P_i, and we give correlation matrices for the widths in the Particle Listings.

(2) We do *not* allow for correlations between input data. We *do* try to pick those ratios and widths that are as independent and as close to the original data as possible. When one experiment measures all the branching fractions and constrains their sum to be one, we leave one of them (usually the least well-determined one) out of the fit to make the set of input data more nearly independent.

(3) We calculate scale factors for both the R_r and P_i when the measurements for any R give a larger-than-expected contribution to the χ^2. According to Eq. (3), the double sum for χ^2 is first summed over experiments $k = 1$ to N_k, leaving a single sum over ratios $\chi^2 = \sum \chi_r^2$. One is tempted to define a scale factor for the ratio r as $S_r^2 = \chi_r^2/\langle\chi_r^2\rangle$. However, since $\langle\chi_r^2\rangle$ is not a fixed quantity (it is somewhere between N_k and N_{k-1}), we do not know how to evaluate this expression. Instead we define

$$S_r^2 = \frac{1}{N_k}\sum_{k=1}^{N_k}\frac{\left(R_{rk}-\overline{R}_r\right)^2}{(\delta R_{rk})^2-(\delta\overline{R}_r)^2}\,, \qquad (4)$$

where $\delta\overline{R}_r$ is the fitted error for ratio r. With this definition the expected value of S_r^2 is one.

The fit is redone using errors for the branching ratios that are scaled by the larger of S_r and unity, from which new and often larger errors $\delta\overline{P}_i'$ are obtained. The scale factors we finally list in such cases are defined by $S_i = \delta\overline{P}_i'/\delta\overline{P}_i$. However, in line with our policy of not letting S affect the central values, we give the values of $\overline{P}_i$ obtained from the original (unscaled) fit.

There is one special case in which the errors that are obtained by the preceding procedure may be changed. When a fitted branching ratio (or rate) $\overline{P}_i$ turns out to be less than three standard deviations $(\delta\overline{P}_i')$ from zero, a new smaller error $(\delta\overline{P}_i'')^-$ is calculated on the low side by requiring the area under the Gaussian between $\overline{P}_i - (\delta\overline{P}_i'')^-$ and $\overline{P}_i$ to be 68.3% of the area between zero and $\overline{P}_i$. A similar correction is made for branching fractions that are within three standard deviations of one. This keeps the quoted errors from overlapping the boundary of the physical region.

4.3. ***Discussion***: The problem of averaging data containing discrepant values is nicely discussed by Taylor in Ref. 4. He considers a number of algorithms that attempt to incorporate inconsistent data into a meaningful average. However, it is difficult to develop a procedure that handles simultaneously in a reasonable way two basic types of situations: (a) data that lie apart from the main body of the data are incorrect (contain unreported errors); and (b) the opposite—it is the main body of data that is incorrect. Unfortunately, as Taylor shows, case (b) is not infrequent. He concludes that the choice of procedure is less significant than the initial choice of data to include or exclude.

We place much emphasis on this choice of data. Often we solicit the help of outside experts (consultants). Sometimes, however, it is simply impossible to determine which of a set of discrepant measurements are correct. Our scale-factor technique is an attempt to address this ignorance by increasing the error. In effect, we are saying that present experiments do not allow a precise determination of this quantity because of unresolvable discrepancies, and one must await further measurements. The reader is warned of this situation by the size of the scale factor, and if he or she desires can go back to the literature (via the Particle Listings) and redo the average with a different choice of data.

Our situation is less severe than most of the cases Taylor considers, such as estimates of the fundamental constants like $\hbar$, *etc.* Most of the errors in his case are dominated by systematic effects. For our data, statistical errors are often at least as large as systematic errors, and statistical errors are usually easier to estimate. A notable exception occurs in partial-wave analyses, where different techniques applied to the same data yield different results. In this case, as stated earlier, we often do not make an average but just quote a range of values.

A brief history of early Particle Data Group averages is given in Ref. 3. Figure 2 shows some histories of our values of a few particle properties. Sometimes large changes occur. These usually reflect the introduction of significant new data or the discarding of older data. Older data are discarded in favor of newer data when it is felt that the newer data have smaller systematic errors, or have more checks on systematic errors, or have made corrections unknown at the time of the older experiments, or simply have much smaller errors. Sometimes, the scale factor becomes large near the time at which a large jump takes place, reflecting the uncertainty introduced by the new and inconsistent data. By and large, however, a full scan of our history plots shows a dull progression toward greater precision at central values quite consistent with the first data points shown.

We conclude that the reliability of the combination of experimental data and our averaging procedures is usually good, but it is important to be aware that fluctuations outside of the quoted errors can and do occur.

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We thank all those who have assisted in the many phases of preparing this *Review*. We particularly thank the many who have responded to our requests for verification of data entered in the Listings, and those who have made suggestions or pointed out errors.

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2. Particle Data Group: M. Aguilar-Benitez *et al.*, Phys. Lett. **170B** (1986).
3. A.H. Rosenfeld, Ann. Rev. Nucl. Sci. **25**, 555 (1975).
4. B.N. Taylor, "Numerical Comparisons of Several Algorithms for Treating Inconsistent Data in a Least-Squares Adjustment of the Fundamental Constants," U.S. National Bureau of Standards NBSIR 81-2426 (1982).

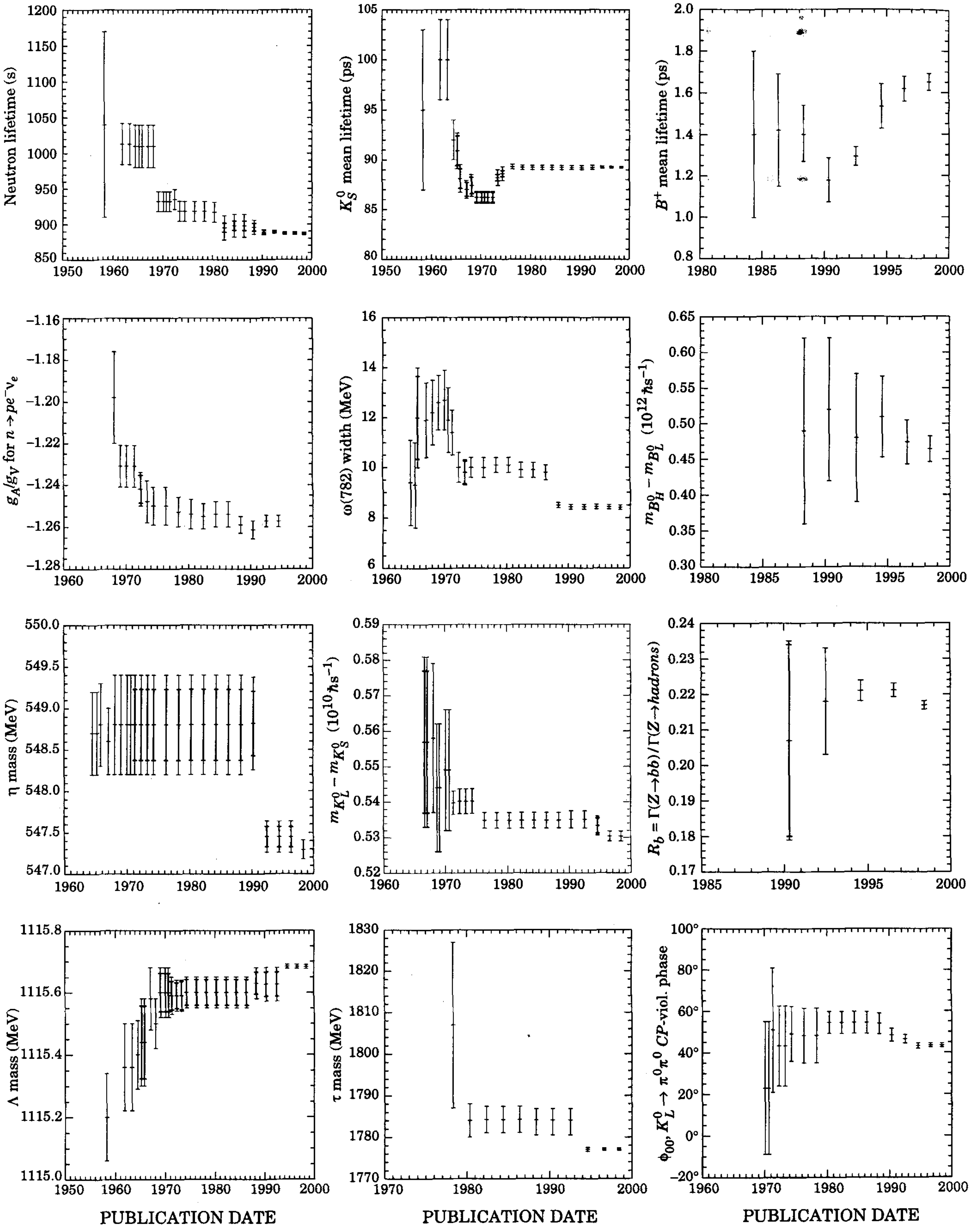

Figure 2: An historical perspective of values of a few particle properties tabulated in this *Review* as a function of date of publication of the *Review*. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the "scale factor."

ONLINE PARTICLE PHYSICS INFORMATION

Revised April 1998 by P. Kreitz (SLAC).

The purpose of this list is to organize a broad set of online catalogs, databases, directories, World-Wide Web (WWW) pages, *etc.*, that are of value to the particle physics physics community. While a substantial amount of particle physics physics information is computer accessible through the Internet's World-Wide Web, most listings do not provide descriptions of a resource's scope and content so that searchers know which source to use for a specific information need. This compilation lists the main information sources with brief annotations and basic Internet WWW addresses (URL's). Because this list must be fixed in print, it is important to consult the updated version of this compilation which includes newly added resources and hypertext links to more complete information at:

`http://www.slac.stanford.edu/library/pdg/hepinfo.html`

In this edition, a resource is excluded if it provides information primarily of interest to one institution. In some cases, multiple databases covering much the same material have been included with the assumption that users will make subsequent choices based on Internet speeds, search system interfaces, or differences in scope, presentation, and coverage. Databases and resources focusing primarily on accelerator physics have been excluded in deference to the excellent compilation at the World Wide Web Virtual Library of Accelerator Physics:

`http://www.slac.stanford.edu/grp/arb/dhw/dpb/w3vl/w3.html`

My thanks to Betty Armstrong, Particle Data Group, Richard Dominiak, SLAC Library, and the many particle physics Web site and database maintainers who have all given me their generous assistance. Please send suggestions, additions, changes, ideas for category groupings, exclusions, *etc.*, via the WWW form linked to the URL above, or by e-mail to `pkreitz@slac.stanford.edu`.

1. Particles & Properties Data:

- REVIEW OF PARTICLE PHYSICS (RPP): A comprehensive review of the field of Particle Physics produced by the Particle Data Group (PDG). Includes a compilation/evaluation of data on particle properties, summary tables with best values and limits for particle properties, extensive summaries of searches for hypothetical particles, and a long section of reviews, tables, and plots on a wide variety of theoretical and experimental topics of interest to particle and astrophysicists. The linked table of contents provides access to particle listings, reviews, summary tables, errata, indices, *etc.* The current printed version is European Physical Journal **C3**, 1 (1998). Maintained at:

  `http://pdg.lbl.gov/`

- PARTICLE PHYSICS BOOKLET: An extract from the most recent edition of the full Review of Particle Physics. Contains images in an easy-to-read print useful for classroom studies:

  `http://pdg.lbl.gov/rpp/booklet/contents.html`

- PARTICLE PROPERTIES Database: Durham/RAL provides a simple index to the PDG particle properties information contained in the Review of Particle Physics. Maintained at:

  `http://durpdg.dur.ac.uk/HEPDATA/PART`

- COMPUTER-READABLE FILES: Currently available from the PDG: tables of masses, widths, and PDG Monte Carlo particle numbers and cross section data, including hadronic total and elastic cross sections vs laboratory momenta and total center-of-mass energy. Overview page at:

  `http://pdg.lbl.gov/computer_read.html`

- PARTICLE PHYSICS DATA SYSTEM: Maintained by the COMPAS group at IHEP, this system, currently under construction, provides an online version of the Guide to Experimental Elementary Particle Physics Literature (1895–1995). Permits searching by author, title, accelerator, detector, reaction, particle, *etc.* For research from 1950 to the present, it will provide online searching of compilations of integrated cross section data and numerical data on observables in reactions. Also provides a chronology of key events in particle physics:

  `http://mesa.lbl.gov:8001/ppds.html`

- REACTION DATA Database: (Durham) This is the main reaction data database containing numerical results for a wide variety of particle physics topics. Included are cross sections (differential and total), polarization measurements, structure functions, spin-density matrices, *etc.*, from e^+e^- annihilation, inclusive hadron and lepton physics, deep inelastic scattering, photoproduction and two-body (and quasi-two-body) scattering. This database is a collaboration of Durham and the COMPAS Group for the PDG.

  `http://durpdg.dur.ac.uk/HEPDATA/REAC`

- PHYSICS AROUND THE WORLD: Reference: From the subsection entitled 'Reference,' choose links to pages of data and tables, fundamental or material constants, physics laws, periodic tables, patents, and standards.

  `http://www.tp.umu.se/TIPTOP/paw`

2. Collaborations & Experiments:

- EXPERIMENTS Database: Contains more than 1,800 experiments in elementary particle physics. Search and browse by author; title; experiment number or prefix; institution; date approved, started or completed; accelerator or detector; polarization, reaction, final state or particle; or by papers produced. Maintained at SLAC for the Particle Data Group. Supplies the information for "Current Experiments in Particle Physics (LBL-91)." Updated every second year (next: Summer 1998):

  `http://www.slac.stanford.edu/find/experiments`

- EXPERIMENTS ONLINE: Home Pages of HEP Experiments: A list from SLAC of accelerator and non-accelerator experiments with an active link to each home page. Accelerator experiments are organized by institution, machine, and experiment name. Non-accelerator experiments are alphabetical by name:

  `http://www.slac.stanford.edu/find/explist.html`

- HIGH ENERGY PHYSICS EXPERIMENTS: A HEPNET page providing links to HEP collaborations around the world. Arranged alphabetically by institution and then collaboration or experiment name:

  `http://www.hep.net/experiments/collabs.html`

3. Conferences:

- CONFERENCES: Contains conferences, schools, and meetings of interest to high-energy physicists with links, when available, to the conference home page. Searchable database produced jointly by the SLAC and DESY libraries of over 8,000 listings covering 1973 to 1999+. Search or browse by title, acronym, date, location. Includes information about published proceedings, links to submitted papers from the SPIRES-HEP database, and links to the electronic versions of the papers if available:

  `http://www.slac.stanford.edu/`
  `spires/form/confspif.html`

- CONFERENCES AND CONFERENCES: (Subtitled: There Are Too Many Conferences!): Lists current and future meetings in many fields of physics. Searchable by research area. Provides links to the conference Web page and the contact. Most useful as a listserv to which you can subscribe to get conference announcements. Web conference pages and an e-mail interface (`robot@physics.umd.edu` with `CONFMENU` in the subject line):

  `http://www.physics.umd.edu/robot/confer/confmenu.html`

- CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS: By The Internet Pilot to Physics. Covers national and regional meetings worldwide for all subfields of physics. Searchable by sub-discipline or by free text words. Provides a Web form and email address for adding a conference. Automatically uploads new entries to the EPS EurophysNet meeting list.

`http://www.tp.umu.se/TIPTOP/FORUM/CONF/`

- EUROPHYSICS MEETINGS LIST: Meta-level international list of other conference lists with active links to the URL'S of the organization's meeting calendar, the conference database, *etc.* Useful for searching by organization, and for providing access to meetings and conferences that are of peripheral interest. Maintained by the European Physical Society. Organized alphabetically by the name of the resource or organization:

  `http://epswww.epfl.ch/conf/urls.html`

- HEP EVENTS: A list maintained by CERN of upcoming conferences, schools, workshops, seminars, and symposia of interest to high-energy physics organized by type of meeting, *e.g.*: school, workshop:

  `http://www.cern.ch/Physics/Conferences`

- PHYSICS CONFERENCE ANNOUNCEMENTS by Thread: Lists current year's conference announcements with links to Web pages. Posting is voluntary. List can be browsed by date, subject, or author:

  `http://xxx.lanl.gov/Announce/Conference/`

4. Current Notices & Announcement Services:

- CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS: By The Internet Pilot to Physics. Provides a Web form or an email address for adding a conference and automatically uploads new entries to the EPS EurophysNet meeting list. Directions on the top-level page enable you to sign up to receive weekly email notification about conferences and deadlines.

  `http://www.tp.umu.se/TIPTOP/FORUM/CONF/`

- CONFNEWS & WEBNEWS: Provides a system for broadcasting a conference or job opening to "a large number of physicists worldwide." For further information, e-mail: `kim@umdhep.umd.edu`

- E-PRINT ARCHIVES Listserv Notices: The LANL-based E-Print Archives provides daily notices of high-energy physics preprints submitted to the archives as full text electronic documents. Use the Web-accessible listings:

  `http://xxx.lanl.gov/`

  or subscribe:

  `http://xxx.lanl.gov/help/subscribe`

Note: Use the library pages below to find announcement lists for recently received preprints, books, and proceedings. Use the online journal links below for journal table of contents. Conference announcements can also be sent via e-mail to most of the conference database providers listed above who often supply their e-mail address at the bottom of their Web pages.

5. Directories:

5.1. *Directories—Research Institutions:*

- CERN RESEARCH INSTITUTES: Contains HEP Institutes used in the CERN Library catalog. Provides addresses, and, where available, the following: phone and fax numbers; e-mail addresses; active Web links; and information about the institution's physics program. Search by free text, organization, country, or town:

  `http://alice.cern.ch/Institutes`

- HEP INSTITUTIONS ONLINE: Active links to the home pages of more than 200 HEP-related institutions with Web servers. Maintained by SLAC. Organized by country, and then alphabetically by institution:

  `http://www.slac.stanford.edu/find/instlink.html`

- INSTITUTIONS: Database of over 5,500 high-energy physics institutes, laboratories, and university departments in which some research on elementary particle physics is performed. Covers six continents and almost one hundred countries. Searchable by name, acronym, location, *etc.* Provides address, phone and fax numbers, and e-mail and Web links where available. Has pointers to the recent HEP papers from an institution. Maintained by SLAC:

  `http://www.slac.stanford.edu/`
  `spires/form/instspif.html`

- DIRECTORY FOR PHYSICS DEPARTMENTS: Maintained by TIPTOP Physics Around the World. Lists departments worldwide. Searchable by field of research or by country or a combination of both.

  `http://www.tp.umu.se/TIPTOP/paw/dsearch.html`

- WWW VIRTUAL LIBRARY—HIGH ENERGY PHYSICS: An alphabetical listing of organizations involved in high-energy physics with links to the institution's Web pages. Maintained by CERN. Because the listings are by institutional acronym or by short name, this is less useful for people unfamiliar with the institution's nickname.

  `http://www.cern.ch/Physics/HEP.html`

5.2. *Directories—People:*

- HEPNAMES: Searchable database of 33,200 e-mail addresses of people related to high-energy physics. Access by individual name, and, in the near future, by institution or place.

  `http://www-spires.slac.stanford.edu/find/hepnames`

  This site is mirrored at Durham under a different name (EMAIL-ID) and with a search interface written and maintained by Durham:

  `http://durpdg.dur.ac.uk/HEPDATA/ID`

- HEP VIRTUAL PHONEBOOK: A list of links to phonebooks and directories of high-energy physics sites and collaborations around the world. Maintained by HEPNET:

  `http://www.hep.net/sites/directories.html`

- US-HEPFOLK: A searchable database of almost 3,500 physicists from 155 U.S. institutions based on a survey conducted in 1997. Searchable by first or last name, by affiliation, and/or by email address. Also provides some interesting demographic plots of the survey data:

  `http://pdg.lbl.gov/us-hepfolk/index.html`

5.3. *Directories—Libraries:*

- Argonne National Lab Library:

  `http://www.ipd.anl.gov/aim/alec/`

- Berkeley Lab (LBNL) Library:

  `http://www-library.lbl.gov/`

- Brookhaven National Lab Library:

  `http://www.bnl.gov/RESLIB/reslib.html`

- (CERN) European Laboratory for Particle Physics Library:

  `http://wwwas.cern.ch/library/library_general/`
  `welcome.html`

- Deutsches Elektronen-Synchrotron (DESY) Library:

  `http://www.desy.de/library/homepage.html`

- Fermilab Library:

  `http://fnalpubs.fnal.gov/library/welcome.html`

- Jefferson Lab Library:

  `http://www.jlab.org/div_dept/admin/library/`

- (KEK) National Laboratory for High Energy Physics Library:
  `http://www-lib.kek.jp/publib.html`
- Lawrence Livermore National Laboratory Library:
  `http://www.llnl.gov/tid/Library.html`
- Los Alamos National Laboratory Library:
  `http://lib-www.lanl.gov/`
- Oak Ridge National Laboratory Library:
  `http://www.ornl.gov/Library/library-home.html`
- Sandia National Laboratory Library:
  `http://www.sandia.gov/library.htm`
- Stanford Linear Accelerator Center Library:
  `http://www.slac.stanford.edu/FIND/spires.html`

5.4. *Directories—Publishers:*

- COMPANIES/PUBLISHERS: Contains 44 links to institutions, societies, or companies involved in supplying physics-related information:
  `http:www.tp.umu.se/TIPTOP/paw/paw.html/`
  `?k=Companies/Publishers&t=k&f=1`
- DIRECTORY OF PUBLISHERS AND VENDORS: Contains hundreds of links to publishers and vendors divided by type (government or university) and by subject. The science section is extensive. Secondary page to "Other Links" leads to more arcane and specialized suppliers and information:
  `http://www.library.vanderbilt.edu/law/acqs/pubr.html`

5.5. *Directories—Scholarly Societies:*

- American Association for the Advancement of Science:
  `http://www.aaas.org/`
- American Association of Physics Teachers:
  `http://www.aapt.org/`
- American Astronomical Society:
  `http://www.aas.org`
- American Institute of Physics:
  `http://aip.org/`
- American Physical Society:
  `http://aps.org`
- American Mathematical Society:
  `http://www.ams.org/`
- European Physical Society:
  `http://epswww.epfl.ch/`
- IEEE Nuclear and Plasma Sciences Society::
  `http://hibp7.ecse.rpi.edu/~connor/ieee/npss.html`
- Institute of Physics:
  `http://www.iop.org/`
- RESOURCES OF SCHOLARLY SOCIETIES—PHYSICS: Maintained by the University of Waterloo Electronic Library's Scholarly Societies Project. Links to the home pages of close to a hundred scholarly societies worldwide. Very up to date:
  `http://www.lib.uwaterloo.ca/society/physics_soc.html`

6. E-Prints/Pre-Prints, Papers, & Reports:

- CERN PREPRINTS CATALOGUE: The CERN Library's database which contains citations to more than 200,000 monographs, series, preprints, and official committee documents held by the Library or the Archives:
  `http://alice.cern.ch/Preprints`

Also provides links to CERN's full text preprint server:
  `http://preprints.cern.ch/weeklist.html#preprints`

- HEP DATABASE (SLAC/SPIRES): Contains over 350,000 bibliographic summaries for particle physics papers (e-prints, journal articles, preprints, reports, theses, *etc.*). Covers 1974 to the present and is updated daily with links to electronic texts (*e.g.* from LANL, CERN, KEK, and other HEP servers). Searchable by all authors and authors' affiliations, title, topic, report number, citation (footnotes), e-print archive number, date, journal, *etc.*: A joint project of the SLAC and DESY libraries with the collaboration of many other research institutions and scholarly societies such as the APS:
  `http://www.slac.stanford.edu/find/hep`
- KISS (KEK Information Service System) for Preprints: KEK Library preprint database. Contains bibliographic records of preprints and technical reports held in the KEK library with links to the full text images of close to 100,000 items in their collection:
  `http://www-lib.kek.jp/KISS.v3/kiss_prepri.html`
- LANL E-PRINT ARCHIVES: An automated electronic repository of physics, mathematics, and nonlinear science preprints. Used heavily by the sub-disciplines of high-energy physics. Began with a core set of archives in 1991. Provides access to the full text of the electronic versions of these preprints. Permits searching by author, title, keyword in abstract. Allows limiting by subfield archive or by date. Papers are sent electronically to the archives by authors:
  `http://xxx.lanl.gov`
- ONE-SHOT WORLD-WIDE PREPRINTS SEARCH: This is a prototype service for a global lookup search throughout most on-line scientific preprint repositories in the world. A very efficient system permitting author or title searching, limiting by year and by broad geographical regions:
  `http://www.ictp.trieste.it/indexes/preprints.html`
- PARTICLE PHYSICS DATA SYSTEM—PPDS: A search interface to the bibliography of the print publication "A Guide to Experimental Elementary Particle Physics Literature" (LBL-90). This bibliography covers the published literature of theoretical and experimental particle physics. Coverage is from 1895 to the present:
  `http://mesa.lbl.gov:8001/ppds.html`
- PPF: PREPRINTS IN PARTICLES AND FIELDS: A weekly listing of approximately 220 new preprints of interest to the high-energy physics community. Contains bibliographic listings for and, in the Web version, full text links to, the new preprints received by and cataloged into the SPIRES-HEP database. Approximately 30% of new titles are not available from the LANL e-print archives. Directions for subscribing to an email version can be found on the page listing the most recent week's preprints received:
  `http://www.slac.stanford.edu/library/documents/newppf.html`

7. Particle Physics Journals & Reviews:

7.1. *Online Journals and Tables of Contents:*

Note: Only a selection of direct title URL's have been listed. Where many titles are available from the same publisher, a link to a summary online journals page from that publisher has been listed. Also please note, some of these journals and publishers may limit access to subscribers; check with your institution's library.

- American Astronomical Society: Astrophysical Journal Electronic Edition:

  `http://www.journals.uchicago.edu/ApJ/`

- American Institute of Physics: The top-level page for their electronic journals may be found at:

  `http://www.aip.org/ojs/service.html`

- American Journal of Physics:

  `http://www.amherst.edu/~ajp/`

- American Physics Society: The top-level page for the APS research journals is:

  `http://publish.aps.org/`

- Elsevier Science (Publishers): The top-level page for Nuclear Physics Electronic is:

  `http://www.nucphys.nl/www/pub/nucphys/npe.html`

- European Physical Society: Their journals are handled by various publishers but may be reached from this top-level page:

  `http://epswww.epfl.ch/pub/index.html`

- Institute of Physics: This page provides links to their online services, electronic journals and magazines, and Physics Express Letters:

  `http://www.iop.org`

- Journal of High Energy Physics: A refereed journal written, run, and distributed by electronic means:

  `http://jhep.sissa.it/`

- Modern Physics Letters: A and B

  `http://www.wspc.com.sg/journals/mpla/mpla.html`
  `http://www.wspc.com.sg/journals/mplb/mplb.html`

- Journal of the Physical Society of Japan:

  `http://wwwsoc.nacsis.ac.jp/jps/jpsj/index.html`

- Springer Publishing: Physics: This link provides a list of Springer journals covering topics of interest to physicists. Small bullets containing the letter 'E' beside each title indicate which journals are also in electronic format:

  `http://link.springer.de/ol/pol/all.htm`

- Physics—Uspekhi

  `http://ufn.ioc.ac.ru/`

- Reviews of Modern Physics

  `http://www.phys.washington.edu/~rmp/Welcome.html`

- Science

  `http://www.sciencemag.org/`

- DESY Library Electronic Journals: Use this Web page for up-to-date links to electronic journals of interest to particle physics. Contains a broader list than is included in this compilation:

  `http://www.desy.de/library/eljnl.html`

- WWW Virtual Library of E-Journals: An excellent source to use when you are wondering if a title is available electronically. This Web site attempts to catalog all electronic journals, newsletters, magazines, and newspapers. Organized by broad subject or source *e.g.*: academic and reviewed journals, email newsletters, political journals. Also permits a title search across all categories:

  `http://www.edoc.com/ejournal/`

7.2. *Online Review Publications:*

- Net Advance of Physics: A free electronic service providing review articles and tutorials in an encyclopedic format. Covers all areas of physics. Includes hypertext links to the items reviewed when available, including e-prints, book announcements, full text of electronic books, and other resources. Welcomes contributions of original review articles:

  `http://web.mit.edu/afs/athena.mit.edu/`
  `user/r/e/redingtn/www/netadv/welcome.html`

- Physics Reports:

  `http://www.elsevier.nl:80/inca/`
  `publications/store/5/0/5/7/0/3`

- Reviews of Modern Physics

  `http://www.phys.washington.edu/~rmp/Welcome.html`

- Particle Physics: An independent online review service providing the field of experimental and theoretical particle physics (including cosmology) with a selected list of preprints from the established public domain preprint servers. Selections are made by independent nomination and then are reviewed by consulting editors. Listed preprints include links to the papers' full text online versions. While hosted by a commercial site, this is an independent and voluntary service for the international physics community.

  `http://www.eagle.co.uk/ppj/home.html`

8. Particle Physics Education Sites:

8.1. *Particle Physics Education: DOE Sites:*

- Argonne National Laboratory Gee Whiz!: Includes links to other interesting and publically-accessible information such as the Rube Goldberg Machine Contest; Arts in Science; and the parts of the movie 'Chain Reaction' that were filmed at Argonne:

  `http://www.anl.gov/OPA/geewhiz.htm`

- Brookhaven National Laboratory: Science Museum Programs:

  `http://www.pubaf.bnl.gov/bnl_museum.htm`

- Contemporary Physics Education Project (CPEP): Provides charts, brochures, Web links, and classroom activities:

  `http://pdg.lbl.gov/cpep.html`

- Center for Particle Astrophysics in Berkeley:

  `http://physics7.berkeley.edu/home.html`

- Fermilab: Education and Outreach Resources for Particle Physicists: Outstanding collection of resources from the 'grandmother' of all physics lab educational programs:

  `http://www-ed.fnal.gov/trc/phys_resc.html`

- Stanford Linear Accelerator Center: Check here soon for the Virtual Visitor's Center:

  `http://www.slac.stanford.edu/gen/edu/education.html`

8.2. *Particle Physics Education: Meta-Sites:*

- ESTEEM: The Department of Energy's exciting and visually appealing meta-site for Education in Science, Technology, Energy, Engineering and Math. Organized both textually and graphically as a 'city'. Users can explore resources by source (energy and science museums), by subject (windmills, 'playground'—virtual experiments, computers), or by targeted audience (university, middle or elementary students). Provides a rich access to many other sites including other meta-sites such as NASA and NSF and and the White House.

  `http://www.sandia.gov/ESTEEM/home.html`

- PhysicsEd: Physics Education Resources: From a group renowned for doing research on physics education. Provides links to courses and topics; curriculum development; resources for demonstrations;

software; research and projects in physics education; textbooks, journals, newsletters, and discussion groups; reference resources, organizations and companies; and much more:

`http://www-hpcc.astro.washington.edu/scied/physics.html`

8.3. *Particle Physics Education: Ask-a-Scientist Sites:*

- Ask A Scientist: Questions are answered by volunteer scientists throughout the world. Service provided by the Newton BBS through Argonne National Lab:

  `http://newton.dep.anl.gov/#AAS`
- Mad Scientist's Network: Ask A Question: Responds to hundreds of questions a week. Contains an extensive archive of answered questions:

  `http://www.madsci.org/submit.html`
- The Science Club: An excellent compilation of places to ask science questions. Organized by 'general' sites and then by sites that specialize in specific subjects or professions:

  `http://www.halcyon.com/sciclub/kidquest.html`

8.4. *Particle Physics Education: Experiments, Demos, & Fun*

- Albert Einstein: A meta-Einstein site with links to dozens of places with resources by and about this scientist:

  `http://www/sas/upenn.edu/~smfriedm/einstein.html`
- Mad Scientist's Network: The Edible/Inedible Experiments Archive: Organized by scientific field. For each experiment, uses common materials and identifies whether the experiment is edible, inedible, or (in one case!?) 'partially drinkable':

  `http://www.madsci.org/experiments/`
- Physics Around the World: There are several useful links to collections of resources on this page, particularly the links to: Hands-On Experiments; Exercises and Problems; and Demonstrations. Targeted to the university level:

  `http://www.tp.umu.se/TIPTOP/paw/`
- Science for the Millenium: Expo Web: Aimed at diverse audiences, this site focuses chiefly on astronomy, astrophysics, advanced computation, and virtual environments to showcase recent advances in these fields. The content is deep and the site is well-designed, permitting hierarchical and serendipitous use. Maintained by NCSA with significant help from the Electronic Visualization Laboratory:

  `http://www.ncsa.uiuc.edu/Cyberia/Expo/information-pavilion.html`
- The Virtual Laboratory : A series of experiments using Java that are targeted at physics classes for non-majors where there are no physical lab sections. The experiments provide conceptual interfaces to the equations of physics and represent interaction with data that simulates a real physics experiment. Includes links to a broader collection of physics experiments:

  `http://physics.hallym.ac.kr/education/oregon/vlab/index.html`

9. Software Directories:

- CERNLIB: CERN PROGRAM LIBRARY: Includes the CERN Program Library (Fortran), a new C++ Libraries (a C++ 'replacement' for CERNLIB), and CERNLIB and related Software including complete programs for GEANT, PAW and PAW++. Also includes links to commercial, free, and other software:

  `http://wwwcn.cern.ch/pl/index.html`
- FREEHEP: A collection of software and information about software useful in high-energy physics. Searching can be done by title, subject, date acquired, or date updated, or by browsing an alphabetical list of all packages:

  `http://heplibw3.slac.stanford.edu:80/FIND/FHMAIN.HTML`
- FERMILAB SOFTWARE TOOLS PROGRAM: Software repository of Fermilab-developed software packages of value to the HEP community. Permits searching for packages by title or subject, by browsing FTP site, and by recent acquisitions:

  `http://www.fnal.gov/fermitools/`
- HEPIC: SOFTWARE AND TOOLS USED IN HEP RESEARCH: A meta-level site with links to major other sites of HEP-related software and computing tools:

  `http://www.hep.net/software.html`
- PHYSICS AROUND THE WORLD: COMPUTING: An excellent meta-list with links to separate Web listings of: software archives; hands-on experiments; graphics & visualization; parallel computing; Java applets; and computing centers. Provides links to other Web compendia of software repositories and directories:

  `http://www.tp.umu.se/TIPTOP/paw/`

SUMMARY TABLES OF PARTICLE PHYSICS

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* There are also search limits in the Summary Tables for the Gauge and Higgs Bosons, the Leptons, the Quarks, and the Mesons.

SUMMARY TABLES OF PARTICLE PROPERTIES

Extracted from the Particle Listings of the
Review of Particle Physics
Published in Eur. Jour. Phys. **C3**, 1 (1998)
Available at `http://pdg.lbl.gov`

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(Approximate closing date for data: January 1, 1998)

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 2 \times 10^{-16}$ eV
Charge $q < 5 \times 10^{-30}$ e
Mean life τ = Stable

g or gluon

$I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

W

$J = 1$

Charge $= \pm 1$ e
Mass $m = 80.41 \pm 0.10$ GeV
$m_Z - m_W = 10.78 \pm 0.10$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.06 \pm 0.06$ GeV

W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.74 ± 0.33) %		–
$e^+\nu$		(10.9 ± 0.4) %		40205
$\mu^+\nu$		(10.2 ± 0.5) %		40205
$\tau^+\nu$		(11.3 ± 0.8) %		40185
hadrons		(67.8 ± 1.0) %		–
$\pi^+\gamma$		$< 2.2 \times 10^{-4}$	95%	40205

Z

$J = 1$

Charge = 0
Mass $m = 91.187 \pm 0.007$ GeV [c]
Full width $\Gamma = 2.490 \pm 0.007$ GeV
$\Gamma(\ell^+\ell^-) = 83.83 \pm 0.27$ MeV [b]
$\Gamma(\text{invisible}) = 498.3 \pm 4.2$ MeV [d]
$\Gamma(\text{hadrons}) = 1740.7 \pm 5.9$ MeV
$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.000 \pm 0.005$
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 0.998 \pm 0.005$ [e]

Average charged multiplicity

$\langle N_{charged} \rangle = 21.00 \pm 0.13$

Couplings to leptons

$g_V^{\ell} = -0.0377 \pm 0.0007$
$g_A^{\ell} = -0.5008 \pm 0.0008$
$g^{\nu_e} = 0.53 \pm 0.09$
$g^{\nu_\mu} = 0.502 \pm 0.017$

Asymmetry parameters [f]

$A_e = 0.1519 \pm 0.0034$
$A_\mu = 0.102 \pm 0.034$
$A_\tau = 0.143 \pm 0.008$
$A_c = 0.59 \pm 0.19$
$A_b = 0.89 \pm 0.11$

Charge asymmetry (%) at Z pole

$A_{FB}^{(0\ell)} = 1.59 \pm 0.18$
$A_{FB}^{(0u)} = 4.0 \pm 7.3$
$A_{FB}^{(0s)} = 9.9 \pm 3.1$ (S = 1.2)
$A_{FB}^{(0c)} = 7.32 \pm 0.58$
$A_{FB}^{(0b)} = 10.02 \pm 0.28$

Z DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-		(3.366 ± 0.008) %		45594
$\mu^+\mu^-$		(3.367 ± 0.013) %		45593
$\tau^+\tau^-$		(3.360 ± 0.015) %		45559
$\ell^+\ell^-$	[b]	(3.366 ± 0.006) %		–
invisible		(20.01 ± 0.16) %		–
hadrons		(69.90 ± 0.15) %		–
$(u\overline{u}+c\overline{c})/2$		(10.1 ± 1.1) %		–
$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(16.6 ± 0.6) %		–
$c\overline{c}$		(12.4 ± 0.6) %		–
$b\overline{b}$		(15.16 ± 0.09) %		–
ggg		< 1.1 %	95%	–
$\pi^0\gamma$		$< 5.2 \times 10^{-5}$	95%	45593
$\eta\gamma$		$< 5.1 \times 10^{-5}$	95%	45592
$\omega\gamma$		$< 6.5 \times 10^{-4}$	95%	45590
$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	95%	45588
$\gamma\gamma$		$< 5.2 \times 10^{-5}$	95%	45594
$\gamma\gamma\gamma$		$< 1.0 \times 10^{-5}$	95%	45594
$\pi^\pm W^\mp$	[g]	$< 7 \times 10^{-5}$	95%	10139
$\rho^\pm W^\mp$	[g]	$< 8.3 \times 10^{-5}$	95%	10114
$J/\psi(1S)X$		$(3.66 \pm 0.23) \times 10^{-3}$		–
$\psi(2S)X$		$(1.60 \pm 0.29) \times 10^{-3}$		–
$\chi_{c1}(1P)X$		$(2.9 \pm 0.7) \times 10^{-3}$		–
$\chi_{c2}(1P)X$		$< 3.2 \times 10^{-3}$	90%	–
$\Upsilon(1S)X + \Upsilon(2S)X + \Upsilon(3S)X$		$(1.0 \pm 0.5) \times 10^{-4}$		–
$\Upsilon(1S)X$		$< 5.5 \times 10^{-5}$	95%	–
$\Upsilon(2S)X$		$< 1.39 \times 10^{-4}$	95%	–
$\Upsilon(3S)X$		$< 9.4 \times 10^{-5}$	95%	–
$(D^0/\overline{D}^0)X$		(20.7 ± 2.0) %		–
$D^\pm X$		(12.2 ± 1.7) %		–
$D^*(2010)^\pm X$	[g]	(11.4 ± 1.3) %		–
$B_s^0 X$		seen		–
anomalous γ+ hadrons	[h]	$< 3.2 \times 10^{-3}$	95%	–
$e^+e^-\gamma$	[h]	$< 5.2 \times 10^{-4}$	95%	45594
$\mu^+\mu^-\gamma$	[h]	$< 5.6 \times 10^{-4}$	95%	45593
$\tau^+\tau^-\gamma$	[h]	$< 7.3 \times 10^{-4}$	95%	45559
$\ell^+\ell^-\gamma\gamma$	[i]	$< 6.8 \times 10^{-6}$	95%	–
$q\overline{q}\gamma\gamma$	[i]	$< 5.5 \times 10^{-6}$	95%	–

Gauge & Higgs Boson Summary Table

$\nu\overline{\nu}\gamma\gamma$		[f] < 3.1	$\times 10^{-6}$	95%	45594
$e^{\pm}\mu^{\mp}$	LF	[g] < 1.7	$\times 10^{-6}$	95%	45593
$e^{\pm}\tau^{\mp}$	LF	[g] < 9.8	$\times 10^{-6}$	95%	45576
$\mu^{\pm}\tau^{\mp}$	LF	[g] < 1.2	$\times 10^{-5}$	95%	45576

Higgs Bosons — H^0 and $H^{\pm}$, Searches for

H^0 Mass $m >$ 77.5 GeV, CL = 95%

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m >$ 62.5 GeV, CL = 95%

A^0 Pseudoscalar Higgs Boson in Supersymmetric Models [j]

Mass $m >$ 62.5 GeV, CL = 95% $\tan\beta > 1$

$H^{\pm}$ Mass $m >$ 54.5 GeV, CL = 95%

See the Particle Listings for a Note giving details of Higgs Bosons.

Heavy Bosons Other Than Higgs Bosons, Searches for

Additional *W* Bosons

W_R — right-handed W
Mass $m >$ 549 GeV
(assuming light right-handed neutrino)
W' with standard couplings decaying to $e\nu$, $\mu\nu$
Mass $m >$ 720 GeV, CL = 95%

Additional *Z* Bosons

Z'_{SM} with standard couplings
Mass $m >$ 690 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 779 GeV, CL = 95% (electroweak fit)
Z_{LR} of $SU(2)_L \times SU(2)_R \times U(1)$
(with $g_L = g_R$)
Mass $m >$ 630 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 389 GeV, CL = 95% (electroweak fit)
Z_χ of $SO(10) \rightarrow SU(5) \times U(1)_\chi$
(coupling constant derived from G.U.T.)
Mass $m >$ 595 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 321 GeV, CL = 95% (electroweak fit)
Z_ψ of $E_6 \rightarrow SO(10) \times U(1)_\psi$
(coupling constant derived from G.U.T.)
Mass $m >$ 590 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 160 GeV, CL = 95% (electroweak fit)
Z_η of $E_6 \rightarrow SU(3) \times SU(2) \times U(1) \times U(1)_\eta$
(coupling constant derived from G.U.T.);
charges are $Q_\eta = \sqrt{3/8}Q_\chi - \sqrt{5/8}Q_\psi$)
Mass $m >$ 620 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 182 GeV, CL = 95% (electroweak fit)

Scalar Leptoquarks

Mass $m >$ 225 GeV, CL = 95% (1st generation, pair prod.)
Mass $m >$ 237 GeV, CL = 95% (1st gener., single prod.)
Mass $m >$ 119 GeV, CL = 95% (2nd gener., pair prod.)
Mass $m >$ 73 GeV, CL = 95% (2nd gener., single prod.)
Mass $m >$ 99 GeV, CL = 95% (3rd gener., pair prod.)
(See the Particle Listings for assumptions on leptoquark quantum numbers and branching fractions.)

Axions (A^0) and Other Very Light Bosons, Searches for

The standard Peccei-Quinn axion is ruled out. Variants with reduced couplings or much smaller masses are constrained by various data. The Particle Listings in the full *Review* contain a Note discussing axion searches.

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is $> 7.2 \times 10^{24}$ years (CL = 90%).

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] Theoretical value. A mass as large as a few MeV may not be precluded.

[b] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[c] The Z-boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies approximately 34 MeV above the real part of the position of the pole (in the energy-squared plane) in the Z-boson propagator.

[d] This partial width takes into account Z decays into $\nu\overline{\nu}$ and any other possible undetected modes.

[e] This ratio has not been corrected for the τ mass.

[f] Here $A \equiv 2g_V g_A/(g_V^2+g_A^2)$.

[g] The value is for the sum of the charge states of particle/antiparticle states indicated.

[h] See the Z Particle Listings for the γ energy range used in this measurement.

[i] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.

[j] The limits assume no invisible decays.

LEPTONS

e

$J = \frac{1}{2}$

Mass $m = 0.51099907 \pm 0.00000015$ MeV [a]
$= (5.485799111 \pm 0.000000012) \times 10^{-4}$ u
$(m_{e^+} - m_{e^-})/m < 4 \times 10^{-8}$, CL = 90%
$|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$
Magnetic moment $\mu = 1.001159652193 \pm 0.000000000010\ \mu_B$
$(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$
Electric dipole moment $d = (0.18 \pm 0.16) \times 10^{-26}$ $e$cm
Mean life $\tau > 4.3 \times 10^{23}$ yr, CL = 68% [b]

μ

$J = \frac{1}{2}$

Mass $m = 105.658389 \pm 0.000034$ MeV [c]
$= 0.113428913 \pm 0.000000017$ u
Mean life $\tau = (2.19703 \pm 0.00004) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.654$ m
Magnetic moment $\mu = 1.0011659230 \pm 0.0000000084\ e\hbar/2m_\mu$
$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}} = (-2.6 \pm 1.6) \times 10^{-8}$
Electric dipole moment $d = (3.7 \pm 3.4) \times 10^{-19}$ $e$cm

Decay parameters [d]

$\rho = 0.7518 \pm 0.0026$
$\eta = -0.007 \pm 0.013$
$\delta = 0.749 \pm 0.004$
$\xi P_\mu = 1.003 \pm 0.008$ [e]
$\xi P_\mu \delta/\rho > 0.99682$, CL = 90% [e]
$\xi' = 1.00 \pm 0.04$
$\xi'' = 0.7 \pm 0.4$
$\alpha/\text{A} = (0 \pm 4) \times 10^{-3}$
$\alpha'/\text{A} = (0 \pm 4) \times 10^{-3}$
$\beta/\text{A} = (4 \pm 6) \times 10^{-3}$
$\beta'/\text{A} = (2 \pm 6) \times 10^{-3}$
$\overline{\eta} = 0.02 \pm 0.08$

μ^+ modes are charge conjugates of the modes below.

μ^- DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$			$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$		[f]	$(1.4 \pm 0.4)\ \%$		53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$		[g]	$(3.4 \pm 0.4) \times 10^{-5}$		53
Lepton Family number (*LF*) violating modes					
$e^- \nu_e \overline{\nu}_\mu$	LF	[h]	$< 1.2\ \%$	90%	53
$e^- \gamma$	LF		$< 4.9 \times 10^{-11}$	90%	53
$e^- e^+ e^-$	LF		$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	LF		$< 7.2 \times 10^{-11}$	90%	53

τ

$J = \frac{1}{2}$

Mass $m = 1777.05^{+0.29}_{-0.26}$ MeV
Mean life $\tau = (290.0 \pm 1.2) \times 10^{-15}$ s
$c\tau = 86.93\ \mu$m
Magnetic moment anomaly > -0.052 and < 0.058, CL = 95%
Electric dipole moment $d > -3.1$ and $< 3.1 \times 10^{-16}$ $e$cm, CL = 95%

Weak dipole moment

$\text{Re}(d^w_\tau) < 0.56 \times 10^{-17}$ $e$cm, CL = 95%
$\text{Im}(d^w_\tau) < 1.5 \times 10^{-17}$ $e$cm, CL = 95%

Weak anomalous magnetic dipole moment

$\text{Re}(\alpha^w_\tau) < 4.5 \times 10^{-3}$, CL = 90%
$\text{Im}(\alpha^w_\tau) < 9.9 \times 10^{-3}$, CL = 90%

Decay parameters

See the τ Particle Listings for a note concerning τ-decay parameters.

$\rho^\tau(e \text{ or } \mu) = 0.748 \pm 0.010$
$\rho^\tau(e) = 0.745 \pm 0.012$
$\rho^\tau(\mu) = 0.741 \pm 0.030$
$\xi^\tau(e \text{ or } \mu) = 1.01 \pm 0.04$
$\xi^\tau(e) = 0.98 \pm 0.05$
$\xi^\tau(\mu) = 1.07 \pm 0.08$
$\eta^\tau(e \text{ or } \mu) = 0.01 \pm 0.07$
$\eta^\tau(\mu) = -0.10 \pm 0.18$
$(\delta\xi)^\tau(e \text{ or } \mu) = 0.749 \pm 0.026$
$(\delta\xi)^\tau(e) = 0.733 \pm 0.033$
$(\delta\xi)^\tau(\mu) = 0.78 \pm 0.05$
$\xi^\tau(\pi) = 0.99 \pm 0.05$
$\xi^\tau(\rho) = 0.996 \pm 0.010$
$\xi^\tau(a_1) = 1.02 \pm 0.04$
$\xi^\tau(\text{all hadronic modes}) = 0.997 \pm 0.009$

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^- \geq 0$ neutrals $\geq 0K^0_L \nu_\tau$ ("1-prong")		$(84.71 \pm 0.13)\ \%$	S=1.2	–
particle$^- \geq 0$ neutrals $\geq 0K^0 \nu_\tau$		$(85.30 \pm 0.13)\ \%$	S=1.2	–
$\mu^- \overline{\nu}_\mu \nu_\tau$	[l]	$(17.37 \pm 0.09)\ \%$		885
$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$	[g]	$(3.0 \pm 0.6) \times 10^{-3}$		–
$e^- \overline{\nu}_e \nu_\tau$	[l]	$(17.81 \pm 0.07)\ \%$		889
$h^- \geq 0$ neutrals $\geq 0K^0_L\ \nu_\tau$		$(49.52 \pm 0.16)\ \%$	S=1.2	–
$h^- \geq 0K^0_L\ \nu_\tau$		$(12.32 \pm 0.12)\ \%$	S=1.5	–
$h^- \nu_\tau$		$(11.79 \pm 0.12)\ \%$	S=1.5	–
$\pi^- \nu_\tau$	[l]	$(11.08 \pm 0.13)\ \%$	S=1.4	883
$K^- \nu_\tau$	[l]	$(7.1 \pm 0.5) \times 10^{-3}$		820
$h^- \geq 1$ neutralsν_τ		$(36.91 \pm 0.17)\ \%$	S=1.2	–
$h^- \pi^0 \nu_\tau$		$(25.84 \pm 0.14)\ \%$	S=1.1	–
$\pi^- \pi^0 \nu_\tau$	[l]	$(25.32 \pm 0.15)\ \%$	S=1.1	878
$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$		878
$K^- \pi^0 \nu_\tau$	[l]	$(5.2 \pm 0.5) \times 10^{-3}$		814
$h^- \geq 2\pi^0 \nu_\tau$		$(10.79 \pm 0.16)\ \%$	S=1.2	–
$h^- 2\pi^0 \nu_\tau$		$(9.39 \pm 0.14)\ \%$	S=1.2	–
$h^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$		$(9.23 \pm 0.14)\ \%$	S=1.2	–
$\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$	[l]	$(9.15 \pm 0.15)\ \%$	S=1.2	862
$K^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$	[l]	$(8.0 \pm 2.7) \times 10^{-4}$		796
$h^- \geq 3\pi^0 \nu_\tau$		$(1.40 \pm 0.11)\ \%$	S=1.1	–
$h^- 3\pi^0 \nu_\tau$		$(1.23 \pm 0.10)\ \%$	S=1.1	–
$\pi^- 3\pi^0 \nu_\tau (\text{ex.}K^0)$	[l]	$(1.11 \pm 0.14)\ \%$		836
$K^- 3\pi^0 \nu_\tau (\text{ex.}K^0)$	[l]	$(4.3\ ^{+10.0}_{-\ 2.9}) \times 10^{-4}$		766
$h^- 4\pi^0 \nu_\tau (\text{ex.}K^0)$		$(1.7 \pm 0.6) \times 10^{-3}$		–
$h^- 4\pi^0 \nu_\tau (\text{ex.}K^0,\eta)$	[l]	$(1.1 \pm 0.6) \times 10^{-3}$		–
$K^- \geq 0\pi^0\ \geq 0K^0\ \nu_\tau$		$(1.66 \pm 0.10)\ \%$		–
$K^- \geq 1\ (\pi^0 \text{ or } K^0)\ \nu_\tau$		$(9.5 \pm 1.0) \times 10^{-3}$		–
Modes with K^0's				
$K^0 (\text{particles})^- \nu_\tau$		$(1.66 \pm 0.09)\ \%$	S=1.4	–
$h^- \overline{K}^0 \geq 0$ neutrals $\geq 0K^0_L \nu_\tau$		$(1.62 \pm 0.09)\ \%$	S=1.4	–
$h^- \overline{K}^0 \nu_\tau$		$(9.9 \pm 0.8) \times 10^{-3}$	S=1.5	–
$\pi^- \overline{K}^0 \nu_\tau$	[l]	$(8.3 \pm 0.8) \times 10^{-3}$	S=1.4	812
$\pi^- \overline{K}^0$ (non-$K^*(892)^-$)ν_τ		$< 1.7 \times 10^{-3}$	CL=95%	812
$K^- K^0 \nu_\tau$	[l]	$(1.59 \pm 0.24) \times 10^{-3}$		737
$h^- \overline{K}^0 \pi^0 \nu_\tau$		$(5.5 \pm 0.5) \times 10^{-3}$		–
$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	[l]	$(3.9 \pm 0.5) \times 10^{-3}$		794
$\overline{K}^0 \rho^- \nu_\tau$		$(1.9 \pm 0.7) \times 10^{-3}$		–
$K^- K^0 \pi^0 \nu_\tau$	[l]	$(1.51 \pm 0.29) \times 10^{-3}$		685
$\pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau$		$(6 \pm 4) \times 10^{-4}$		–
$K^- K^0 \pi^0 \pi^0 \nu_\tau$		$< 3.9 \times 10^{-4}$	CL=95%	–
$\pi^- K^0 \overline{K}^0 \nu_\tau$	[l]	$(1.21 \pm 0.21) \times 10^{-3}$	S=1.2	682

$\pi^- K^0_S K^0_S \nu_\tau$		$(3.0 \pm 0.5) \times 10^{-4}$	S=1.2	–
$\pi^- K^0_S K^0_L \nu_\tau$		$(6.0 \pm 1.0) \times 10^{-4}$	S=1.2	–
$\pi^- K^0_S K^0_S \pi^0 \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%	–
$\pi^- K^0_S K^0_L \pi^0 \nu_\tau$		$(3.1 \pm 1.2) \times 10^{-4}$		–
$K^- K^0 \geq 0$ neutrals ν_τ		$(3.1 \pm 0.4) \times 10^{-3}$		–
$K^0 h^+ h^- h^- \geq 0$ neutrals ν_τ		$< 1.7 \times 10^{-3}$	CL=95%	–
$K^0 h^+ h^- h^- \nu_\tau$		$(2.3 \pm 2.0) \times 10^{-4}$		–

Modes with three charged particles

$h^- h^- h^+ \geq$ 0neut. ν_τ ("3-prong")		(15.18 ± 0.13) %	S=1.2	–
$h^- h^- h^+ \geq 0$ neutrals ν_τ (ex. $K^0_S \rightarrow \pi^+ \pi^-$)		(14.60 ± 0.13) %	S=1.2	–
$\pi^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		(14.60 ± 0.14) %		–
$h^- h^- h^+ \nu_\tau$		(9.96 ± 0.10) %	S=1.1	–
$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.62 ± 0.10) %	S=1.1	–
$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)		(9.57 ± 0.10) %	S=1.1	–
$\pi^- \pi^+ \pi^- \nu_\tau$		(9.56 ± 0.11) %	S=1.1	–
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)		(9.52 ± 0.11) %	S=1.1	–
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0,ω)	[*l*]	(9.23 ± 0.11) %	S=1.1	–
$h^- h^- h^+ \geq 1$ neutrals ν_τ		(5.18 ± 0.11) %	S=1.2	–
$h^- h^- h^+ \geq 1$ neutrals ν_τ (ex. $K^0_S \rightarrow \pi^+ \pi^-$)		(4.98 ± 0.11) %	S=1.2	–
$h^- h^- h^+ \pi^0 \nu_\tau$		(4.50 ± 0.09) %	S=1.1	–
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.31 ± 0.09) %	S=1.1	–
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)		(2.59 ± 0.09) %		–
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		(4.35 ± 0.10) %		–
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		(4.22 ± 0.10) %		–
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0,ω)	[*l*]	(2.49 ± 0.10) %		–
$h^- (\rho \pi)^0 \nu_\tau$		(2.88 ± 0.35) %		–
$(a_1(1260) h)^- \nu_\tau$		< 2.0 %	CL=95%	–
$h^- \rho \pi^0 \nu_\tau$		(1.35 ± 0.20) %		–
$h^- \rho^+ h^- \nu_\tau$		$(4.5 \pm 2.2) \times 10^{-3}$		–
$h^- \rho^- h^+ \nu_\tau$		(1.17 ± 0.23) %		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$		$(5.4 \pm 0.4) \times 10^{-3}$		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0)		$(5.3 \pm 0.4) \times 10^{-3}$		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0,ω,η)	[*l*]	$(1.1 \pm 0.4) \times 10^{-3}$		–
$h^- h^- h^+ \geq 3\pi^0 \nu_\tau$	[*l*]	$(1.4 {}^{+0.9}_{-0.7}) \times 10^{-3}$	S=1.5	–
$h^- h^- h^+ 3\pi^0 \nu_\tau$		$(2.9 \pm 0.8) \times 10^{-4}$		–
$K^- h^+ h^- \geq 0$ neutrals ν_τ		$(5.4 \pm 0.7) \times 10^{-3}$	S=1.1	–
$K^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		$(3.1 \pm 0.6) \times 10^{-3}$	S=1.1	–
$K^- \pi^+ \pi^- \nu_\tau$		$(2.3 \pm 0.4) \times 10^{-3}$		–
$K^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)	[*l*]	$(1.8 \pm 0.5) \times 10^{-3}$		–
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$		$(8 \pm 4) \times 10^{-4}$		–
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)	[*l*]	$(2.4 {}^{+4.3}_{-1.6}) \times 10^{-4}$		–
$K^- \pi^+ K^- \geq 0$ neut. ν_τ		$< 9 \times 10^{-4}$	CL=95%	–
$K^- K^+ \pi^- \geq 0$ neut. ν_τ		$(2.3 \pm 0.4) \times 10^{-3}$		–
$K^- K^+ \pi^- \nu_\tau$	[*l*]	$(1.61 \pm 0.26) \times 10^{-3}$		685
$K^- K^+ \pi^- \pi^0 \nu_\tau$	[*l*]	$(6.9 \pm 3.0) \times 10^{-4}$		–
$K^- K^+ K^- \geq 0$ neut. ν_τ		$< 2.1 \times 10^{-3}$	CL=95%	–
$K^- K^+ K^- \nu_\tau$		$< 1.9 \times 10^{-4}$	CL=90%	–
$\pi^- K^+ \pi^- \geq 0$ neut. ν_τ		$< 2.5 \times 10^{-3}$	CL=95%	–
$e^- e^- e^+ \overline{\nu}_e \nu_\tau$		$(2.8 \pm 1.5) \times 10^{-5}$		889
$\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau$		$< 3.6 \times 10^{-5}$	CL=90%	885

Modes with five charged particles

$3h^- 2h^+ \geq 0$ neutrals ν_τ (ex. $K^0_S \rightarrow \pi^- \pi^+$) ("5-prong")		$(9.7 \pm 0.7) \times 10^{-4}$		–
$3h^- 2h^+ \nu_\tau$ (ex.K^0)	[*l*]	$(7.5 \pm 0.7) \times 10^{-4}$		–
$3h^- 2h^+ \pi^0 \nu_\tau$ (ex.K^0)	[*l*]	$(2.2 \pm 0.5) \times 10^{-4}$		–
$3h^- 2h^+ 2\pi^0 \nu_\tau$		$< 1.1 \times 10^{-4}$	CL=90%	–

Miscellaneous other allowed modes

$(5\pi)^- \nu_\tau$		$(7.4 \pm 0.7) \times 10^{-3}$		–
$4h^- 3h^+ \geq 0$ neutrals ν_τ ("7-prong")		$< 2.4 \times 10^{-6}$	CL=90%	–
$K^*(892)^- \geq 0 (h^0 \neq K^0_S) \nu_\tau$		(1.94 ± 0.31) %		–
$K^*(892)^- \geq 0$ neutrals ν_τ		(1.33 ± 0.13) %		–
$K^*(892)^- \nu_\tau$		(1.28 ± 0.08) %		665
$K^*(892)^0 K^- \geq 0$ neutrals ν_τ		$(3.2 \pm 1.4) \times 10^{-3}$		–
$K^*(892)^0 K^- \nu_\tau$		$(2.1 \pm 0.4) \times 10^{-3}$		539
$\overline{K}^*(892)^0 \pi^- \geq 0$ neutrals ν_τ		$(3.8 \pm 1.7) \times 10^{-3}$		–
$\overline{K}^*(892)^0 \pi^- \nu_\tau$		$(2.2 \pm 0.5) \times 10^{-3}$		653
$(\overline{K}^*(892) \pi)^- \nu_\tau \rightarrow \pi^- \overline{K}^0 \pi^0 \nu_\tau$		$(1.1 \pm 0.5) \times 10^{-3}$		–
$K_1(1270)^- \nu_\tau$		$(4 \pm 4) \times 10^{-3}$		433
$K_1(1400)^- \nu_\tau$		$(8 \pm 4) \times 10^{-3}$		335
$K_2^*(1430)^- \nu_\tau$		$< 3 \times 10^{-3}$	CL=95%	317
$\eta \pi^- \nu_\tau$		$< 1.4 \times 10^{-4}$	CL=95%	798
$\eta \pi^- \pi^0 \nu_\tau$	[*l*]	$(1.74 \pm 0.24) \times 10^{-3}$		778
$\eta \pi^- \pi^0 \pi^0 \nu_\tau$		$(1.4 \pm 0.7) \times 10^{-4}$		746
$\eta K^- \nu_\tau$		$(2.7 \pm 0.6) \times 10^{-4}$		720
$\eta \pi^+ \pi^- \pi^- \geq 0$ neutrals ν_τ		$< 3 \times 10^{-3}$	CL=90%	–
$\eta \pi^- \pi^+ \pi^- \nu_\tau$		$(3.4 \pm 0.8) \times 10^{-4}$		–
$\eta a_1(1260)^- \nu_\tau \rightarrow \eta \pi^- \rho^0 \nu_\tau$		$< 3.9 \times 10^{-4}$	CL=90%	–
$\eta \eta \pi^- \nu_\tau$		$< 1.1 \times 10^{-4}$	CL=95%	637
$\eta \eta \pi^- \pi^0 \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%	559
$\eta'(958) \pi^- \nu_\tau$		$< 7.4 \times 10^{-5}$	CL=90%	–
$\eta'(958) \pi^- \pi^0 \nu_\tau$		$< 8.0 \times 10^{-5}$	CL=90%	–
$\phi \pi^- \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=90%	585
$\phi K^- \nu_\tau$		$< 6.7 \times 10^{-5}$	CL=90%	–
$f_1(1285) \pi^- \nu_\tau$		$(5.8 \pm 2.3) \times 10^{-4}$		–
$f_1(1285) \pi^- \nu_\tau \rightarrow \eta \pi^- \pi^+ \pi^- \nu_\tau$		$(1.9 \pm 0.7) \times 10^{-4}$		–
$h^- \omega \geq 0$ neutrals ν_τ		(2.36 ± 0.08) %		–
$h^- \omega \nu_\tau$	[*l*]	(1.93 ± 0.06) %		–
$h^- \omega \pi^0 \nu_\tau$	[*l*]	$(4.3 \pm 0.5) \times 10^{-3}$		–
$h^- \omega 2\pi^0 \nu_\tau$		$(1.9 \pm 0.8) \times 10^{-4}$		–

Lepton Family number (*LF*), Lepton number (*L*), or Baryon number (*B*) violating modes (In the modes below, ℓ means a sum over *e* and μ modes)

L means lepton number violation (*e.g.* $\tau^- \rightarrow e^+ \pi^- \pi^-$). Following common usage, *LF* means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \rightarrow e^- \pi^+ \pi^-$). *B* means baryon number violation.

$e^- \gamma$	*LF*	$< 2.7 \times 10^{-6}$	CL=90%	888
$\mu^- \gamma$	*LF*	$< 3.0 \times 10^{-6}$	CL=90%	885
$e^- \pi^0$	*LF*	$< 3.7 \times 10^{-6}$	CL=90%	883
$\mu^- \pi^0$	*LF*	$< 4.0 \times 10^{-6}$	CL=90%	880
$e^- K^0$	*LF*	$< 1.3 \times 10^{-3}$	CL=90%	819
$\mu^- K^0$	*LF*	$< 1.0 \times 10^{-3}$	CL=90%	815
$e^- \eta$	*LF*	$< 8.2 \times 10^{-6}$	CL=90%	804
$\mu^- \eta$	*LF*	$< 9.6 \times 10^{-6}$	CL=90%	800
$e^- \rho^0$	*LF*	$< 2.0 \times 10^{-6}$	CL=90%	722
$\mu^- \rho^0$	*LF*	$< 6.3 \times 10^{-6}$	CL=90%	718
$e^- K^*(892)^0$	*LF*	$< 5.1 \times 10^{-6}$	CL=90%	663
$\mu^- K^*(892)^0$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%	657
$e^- \overline{K}^*(892)^0$	*LF*	$< 7.4 \times 10^{-6}$	CL=90%	663
$\mu^- \overline{K}^*(892)^0$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%	657
$e^- \phi$	*LF*	$< 6.9 \times 10^{-6}$	CL=90%	596
$\mu^- \phi$	*LF*	$< 7.0 \times 10^{-6}$	CL=90%	590
$\pi^- \gamma$	*L*	$< 2.8 \times 10^{-4}$	CL=90%	883
$\pi^- \pi^0$	*L*	$< 3.7 \times 10^{-4}$	CL=90%	878
$e^- e^+ e^-$	*LF*	$< 2.9 \times 10^{-6}$	CL=90%	888
$e^- \mu^+ \mu^-$	*LF*	$< 1.8 \times 10^{-6}$	CL=90%	882
$e^+ \mu^- \mu^-$	*LF*	$< 1.5 \times 10^{-6}$	CL=90%	882
$\mu^- e^+ e^-$	*LF*	$< 1.7 \times 10^{-6}$	CL=90%	885
$\mu^+ e^- e^-$	*LF*	$< 1.5 \times 10^{-6}$	CL=90%	885
$\mu^- \mu^+ \mu^-$	*LF*	$< 1.9 \times 10^{-6}$	CL=90%	873
$e^- \pi^+ \pi^-$	*LF*	$< 2.2 \times 10^{-6}$	CL=90%	877
$e^+ \pi^- \pi^-$	*L*	$< 1.9 \times 10^{-6}$	CL=90%	877
$\mu^- \pi^+ \pi^-$	*LF*	$< 8.2 \times 10^{-6}$	CL=90%	866
$\mu^+ \pi^- \pi^-$	*L*	$< 3.4 \times 10^{-6}$	CL=90%	866
$e^- \pi^+ K^-$	*LF*	$< 6.4 \times 10^{-6}$	CL=90%	814
$e^- \pi^- K^+$	*LF*	$< 3.8 \times 10^{-6}$	CL=90%	814
$e^+ \pi^- K^-$	*L*	$< 2.1 \times 10^{-6}$	CL=90%	814
$e^- K^+ K^-$	*LF*	$< 6.0 \times 10^{-6}$	CL=90%	739
$e^+ K^- K^-$	*L*	$< 3.8 \times 10^{-6}$	CL=90%	739
$\mu^- \pi^+ K^-$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%	800
$\mu^- \pi^- K^+$	*LF*	$< 7.4 \times 10^{-6}$	CL=90%	800
$\mu^+ \pi^- K^-$	*L*	$< 7.0 \times 10^{-6}$	CL=90%	800
$\mu^- K^+ K^-$	*LF*	$< 1.5 \times 10^{-5}$	CL=90%	699
$\mu^+ K^- K^-$	*L*	$< 6.0 \times 10^{-6}$	CL=90%	699
$e^- \pi^0 \pi^0$	*LF*	$< 6.5 \times 10^{-6}$	CL=90%	878
$\mu^- \pi^0 \pi^0$	*LF*	$< 1.4 \times 10^{-5}$	CL=90%	867
$e^- \eta \eta$	*LF*	$< 3.5 \times 10^{-5}$	CL=90%	700
$\mu^- \eta \eta$	*LF*	$< 6.0 \times 10^{-5}$	CL=90%	654
$e^- \pi^0 \eta$	*LF*	$< 2.4 \times 10^{-5}$	CL=90%	798
$\mu^- \pi^0 \eta$	*LF*	$< 2.2 \times 10^{-5}$	CL=90%	784
$\overline{p} \gamma$	*L,B*	$< 2.9 \times 10^{-4}$	CL=90%	641
$\overline{p} \pi^0$	*L,B*	$< 6.6 \times 10^{-4}$	CL=90%	632
$\overline{p} \eta$	*L,B*	$< 1.30 \times 10^{-3}$	CL=90%	476
e^- light boson	*LF*	$< 2.7 \times 10^{-3}$	CL=95%	–
μ^- light boson	*LF*	$< 5 \times 10^{-3}$	CL=95%	–

Heavy Charged Lepton Searches

$L^\pm$ – charged lepton

Mass $m >$ 80.2 GeV, CL = 95% $m_\nu \approx 0$

$L^\pm$ – stable charged heavy lepton

Mass $m >$ 84.2 GeV, CL = 95%

Neutrinos

See the Particle Listings for a Note "Neutrino Mass" giving details of neutrinos, masses, mixing, and the status of experimental searches.

ν_e

$J = \frac{1}{2}$

Mass m: Unexplained effects have resulted in significantly negative m^2 in the new, precise tritium beta decay experiments. It is felt that a real neutrino mass as large as 10–15 eV would cause observable spectral distortions even in the presence of the end-point count excesses.

Mean life/mass, $\tau/m_{\nu_e} > 7 \times 10^9$ s/eV (solar)

Mean life/mass, $\tau/m_{\nu_e} > 300$ s/eV, CL = 90% (reactor)

Magnetic moment $\mu < 1.8 \times 10^{-10}\ \mu_B$, CL = 90%

ν_μ

$J = \frac{1}{2}$

Mass $m <$ 0.17 MeV, CL = 90%

Mean life/mass, $\tau/m_{\nu_\mu} > 15.4$ s/eV, CL = 90%

Magnetic moment $\mu < 7.4 \times 10^{-10}\ \mu_B$, CL = 90%

ν_τ

$J = \frac{1}{2}$

Mass $m <$ 18.2 MeV, CL = 95%

Magnetic moment $\mu < 5.4 \times 10^{-7}\ \mu_B$, CL = 90%

Electric dipole moment $d < 5.2 \times 10^{-17}$ $e$cm, CL = 95%

Number of Light Neutrino Types

(including ν_e, ν_μ, and ν_τ)

Number $N = 2.994 \pm 0.012$ (Standard Model fits to LEP data)

Number $N = 3.07 \pm 0.12$ (Direct measurement of invisible Z width)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note "Neutrino Mass" giving details of neutrinos, masses, mixing, and the status of experimental searches.

While no direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained, suggestive evidence has come from solar neutrino observations, from anomalies in the relative fractions of ν_e and ν_μ observed in energetic cosmic-ray air showers, and possibly from a $\overline{\nu}_e$ appearance experiment at Los Alamos. Sample limits are:

Stable Neutral Heavy Lepton Mass Limits

Mass $m >$ 45.0 GeV, CL = 95% (Dirac)

Mass $m >$ 39.5 GeV, CL = 95% (Majorana)

Neutral Heavy Lepton Mass Limits

Mass $m >$ 69.0 GeV, CL = 95% (Dirac ν_L coupling to e, μ, τ with $|U_{\ell J}|^2 > 10^{-12}$)

Mass $m >$ 58.2 GeV, CL = 95% (Majorana ν_L coupling to e, μ, τ with $|U_{\ell J}|^2 > 10^{-12}$)

Solar Neutrinos

Detectors using gallium ($E_\nu \gtrsim 0.2$ MeV), chlorine ($E_\nu \gtrsim 0.8$ MeV), and Čerenkov effect in water ($E_\nu \gtrsim 7$ MeV) measure significantly lower neutrino rates than are predicted from solar models. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with $\Delta m^2 \leq 10^{-5}$ eV^2 causing the disappearance of ν_e.

Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This could be explained by oscillations leading to the disappearance of ν_μ with $\Delta m^2 \approx 10^{-3}$ to 10^{-2} eV^2.

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$ (θ = mixing angle)

$\Delta m^2 < 9 \times 10^{-4}$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: ν_μ ($\overline{\nu}_\mu$) → ν_e ($\overline{\nu}_e$) (any combination)

$\Delta m^2 < 0.075$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)

$\sin^2 2\theta < 1.8 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] The uncertainty in the electron mass in unified atomic mass units (u) is ten times smaller than that given by the 1986 CODATA adjustment, quoted in the Table of Physical Constants (Section 1). The conversion to MeV via the factor 931.49432(28) MeV/u is more uncertain because of the electron charge uncertainty. Our value in MeV differs slightly from the 1986 CODATA result.

[b] This is the best "electron disappearance" limit. The best limit for the mode $e^- \to \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

[c] The muon mass is most precisely known in u (unified atomic mass units). The conversion factor to MeV via the factor 931.49432(28) MeV/u is more uncertain because of the electron charge uncertainty.

[d] See the "Note on Muon Decay Parameters" in the μ Particle Listings for definitions and details.

[e] P_μ is the longitudinal polarization of the muon from pion decay. In standard $V{-}A$ theory, $P_\mu = 1$ and $\rho = \delta = 3/4$.

[f] This only includes events with the γ energy > 10 MeV. Since the $e^- \overline{\nu}_e \nu_\mu$ and $e^- \overline{\nu}_e \nu_\mu \gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[g] See the μ Particle Listings for the energy limits used in this measurement.

[h] A test of additive vs. multiplicative lepton family number conservation.

[i] Basis mode for the τ.

Quark Summary Table

QUARKS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass-independent subtraction scheme such as $\overline{\text{MS}}$ at a scale $\mu \approx 2$ GeV. The *c*- and *b*-quark masses are estimated from charmonium, bottomonium, *D*, and *B* masses. They are the "running" masses in the $\overline{\text{MS}}$ scheme. These can be different from the heavy quark masses obtained in potential models.

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1.5 to 5 MeV [a] Charge = $\frac{2}{3}\,e$ $I_z = +\frac{1}{2}$
m_u/m_d = 0.20 to 0.70

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 3 to 9 MeV [a] Charge = $-\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$
m_s/m_d = 17 to 25
$\overline{m} = (m_u+m_d)/2$ = 2 to 6 MeV

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 60 to 170 MeV [a] Charge = $-\frac{1}{3}\,e$ Strangeness = −1
$(m_s - (m_u + m_d)/2)/(m_d - m_u)$ = 34 to 51

c

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1.1 to 1.4 GeV Charge = $\frac{2}{3}\,e$ Charm = +1

b

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 4.1 to 4.4 GeV Charge = $-\frac{1}{3}\,e$ Bottom = −1

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}\,e$ Top = +1

Mass $m = 173.8 \pm 5.2$ GeV (direct observation of top events)
Mass $m = 170 \pm 7$ (+14) GeV (Standard Model electroweak fit, assuming $M_H = M_Z$. Number in parentheses is shift from changing M_H to 300 GeV.

b′ (4th Generation) Quark, Searches for

Mass $m >$ 128 GeV, CL = 95% ($p\overline{p}$, charged current decays)
Mass $m >$ 46.0 GeV, CL = 95% (e^+e^-, all decays)

Free Quark Searches

All searches since 1977 have had negative results.

NOTES

[a] The ratios m_u/m_d and m_s/m_d are extracted from pion and kaon masses using chiral symmetry. The estimates of *u* and *d* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.56995 \pm 0.00035$ MeV
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0116 \pm 0.0016$ (S = 1.3)
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b] (99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$		[c] $(1.24 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b] $(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c] $(1.61 \pm 0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.025 \pm 0.034) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
$\mu^+\overline{\nu}_e$	*L*	[d] $< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d] $< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*	$< 1.6 \times 10^{-6}$	90%	30

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9764 \pm 0.0006$ MeV
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.1$ nm

π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.798 ± 0.032) %	S=1.1	67
$e^+e^-\gamma$		(1.198 ± 0.032) %	S=1.1	67
γ positronium		$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$		$(3.14 \pm 0.30) \times 10^{-5}$		67
e^+e^-		$(7.5 \pm 2.0) \times 10^{-8}$		67
4γ		$< 2 \times 10^{-8}$	CL=90%	67
$\nu\overline{\nu}$		[e] $< 8.3 \times 10^{-7}$	CL=90%	67
$\nu_e\overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\overline{\nu}_\mu$		$< 3.1 \times 10^{-6}$	CL=90%	67
$\nu_\tau\overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%	67
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
3γ	*C*	$< 3.1 \times 10^{-8}$	CL=90%	67
$\mu^+e^- + e^-\mu^+$	*LF*	$< 1.72 \times 10^{-8}$	CL=90%	26

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.30 \pm 0.12$ MeV
Full width $\Gamma = 1.18 \pm 0.11$ keV [f] (S = 1.8)

C-nonconserving decay parameters

$\pi^+\pi^-\pi^0$ Left-right asymmetry = $(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Sextant asymmetry = $(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Quadrant asymmetry = $(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ Left-right asymmetry = $(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ β (*D*-wave) = 0.05 ± 0.06 (S = 1.5)

Dalitz plot parameter

$\pi^0\pi^0\pi^0$ $\alpha = -0.039 \pm 0.015$

η DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes				
neutral modes		(71.5 ± 0.6) %	S=1.4	–
2γ		[f] (39.21 ± 0.34) %	S=1.4	274
$3\pi^0$		(32.2 ± 0.4) %	S=1.3	178
$\pi^0 2\gamma$		$(7.1 \pm 1.4) \times 10^{-4}$		257
other neutral modes		< 2.8 %	CL=90%	–
Charged modes				
charged modes		(28.5 ± 0.6) %	S=1.4	–
$\pi^+\pi^-\pi^0$		(23.1 ± 0.5) %	S=1.4	173
$\pi^+\pi^-\gamma$		(4.77 ± 0.13) %	S=1.3	235
$e^+e^-\gamma$		$(4.9 \pm 1.1) \times 10^{-3}$		274
$\mu^+\mu^-\gamma$		$(3.1 \pm 0.4) \times 10^{-4}$		252
e^+e^-		$< 7.7 \times 10^{-5}$	CL=90%	274
$\mu^+\mu^-$		$(5.8 \pm 0.8) \times 10^{-6}$		252
$\pi^+\pi^-e^+e^-$		$(1.3^{+1.2}_{-0.8}) \times 10^{-3}$		235
$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$		235
$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%	173
$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%	210
Charge conjugation (*C*), Parity (*P*), Charge conjugation × Parity (*CP*), or Lepton Family number (*LF*) violating modes				
$\pi^+\pi^-$	*P,CP*	$< 9 \times 10^{-4}$	CL=90%	235
3γ	*C*	$< 5 \times 10^{-4}$	CL=95%	274
$\pi^0e^+e^-$	*C*	[g] $< 4 \times 10^{-5}$	CL=90%	257
$\pi^0\mu^+\mu^-$	*C*	[g] $< 5 \times 10^{-6}$	CL=90%	210
$\mu^+e^- + \mu^-e^+$	*LF*	$< 6 \times 10^{-6}$	CL=90%	263

$f_0(400\text{–}1200)$ [h] or σ

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}1200)$ MeV
Full width $\Gamma = (600\text{–}1000)$ MeV

$f_0(400\text{–}1200)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	–
$\gamma\gamma$	seen	–

$\rho(770)$ [l]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 770.0 \pm 0.8$ MeV (S = 1.8)
Full width $\Gamma = 150.7 \pm 1.1$ MeV
$\Gamma_{ee} = 6.77 \pm 0.32$ keV

$\rho(770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	~ 100 %		358
$\rho(770)^{\pm}$ decays			
$\pi^{\pm}\gamma$	$(4.5 \pm 0.5) \times 10^{-4}$	S=2.2	372
$\pi^{\pm}\eta$	$< 6 \times 10^{-3}$	CL=84%	146
$\pi^{\pm}\pi^{+}\pi^{-}\pi^{0}$	$< 2.0 \times 10^{-3}$	CL=84%	249
$\rho(770)^{0}$ decays			
$\pi^{+}\pi^{-}\gamma$	$(9.9 \pm 1.6) \times 10^{-3}$		358
$\pi^{0}\gamma$	$(6.8 \pm 1.7) \times 10^{-4}$		372
$\eta\gamma$	$(2.4 ^{+0.8}_{-0.9}) \times 10^{-4}$	S=1.6	189
$\mu^{+}\mu^{-}$	[j] $(4.60 \pm 0.28) \times 10^{-5}$		369
$e^{+}e^{-}$	[j] $(4.49 \pm 0.22) \times 10^{-5}$		384
$\pi^{+}\pi^{-}\pi^{0}$	$< 1.2 \times 10^{-4}$	CL=90%	319
$\pi^{+}\pi^{-}\pi^{+}\pi^{-}$	$< 2 \times 10^{-4}$	CL=90%	246
$\pi^{+}\pi^{-}\pi^{0}\pi^{0}$	$< 4 \times 10^{-5}$	CL=90%	252

$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 781.94 \pm 0.12$ MeV (S = 1.5)
Full width $\Gamma = 8.41 \pm 0.09$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

$\omega(782)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^{+}\pi^{-}\pi^{0}$		(88.8 ± 0.7) %		327
$\pi^{0}\gamma$		(8.5 ± 0.5) %		379
$\pi^{+}\pi^{-}$		(2.21 ± 0.30) %		365
neutrals (excluding $\pi^{0}\gamma$)		$(5.3 ^{+8.7}_{-3.5}) \times 10^{-3}$		–
$\eta\gamma$		$(6.5 \pm 1.0) \times 10^{-4}$		199
$\pi^{0}e^{+}e^{-}$		$(5.9 \pm 1.9) \times 10^{-4}$		379
$\pi^{0}\mu^{+}\mu^{-}$		$(9.6 \pm 2.3) \times 10^{-5}$		349
$e^{+}e^{-}$		$(7.07 \pm 0.19) \times 10^{-5}$	S=1.1	391
$\pi^{+}\pi^{-}\pi^{0}\pi^{0}$		< 2 %	CL=90%	261
$\pi^{+}\pi^{-}\gamma$		$< 3.6 \times 10^{-3}$	CL=95%	365
$\pi^{+}\pi^{-}\pi^{+}\pi^{-}$		$< 1 \times 10^{-3}$	CL=90%	256
$\pi^{0}\pi^{0}\gamma$		$(7.2 \pm 2.5) \times 10^{-5}$		367
$\mu^{+}\mu^{-}$		$< 1.8 \times 10^{-4}$	CL=90%	376
3γ		$< 1.9 \times 10^{-4}$	CL=95%	391
Charge conjugation (C) violating modes				
$\eta\pi^{0}$	C	$< 1 \times 10^{-3}$	CL=90%	162
$3\pi^{0}$	C	$< 3 \times 10^{-4}$	CL=90%	329

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.78 \pm 0.14$ MeV
Full width $\Gamma = 0.203 \pm 0.016$ MeV (S = 1.3)

$\eta'(958)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^{+}\pi^{-}\eta$		(43.8 ± 1.5) %	S=1.1	232
$\rho^{0}\gamma$ (including non-resonant $\pi^{+}\pi^{-}\gamma$)		(30.2 ± 1.3) %	S=1.1	169
$\pi^{0}\pi^{0}\eta$		(20.7 ± 1.3) %	S=1.2	239
$\omega\gamma$		(3.01 ± 0.30) %		160
$\gamma\gamma$		(2.11 ± 0.13) %	S=1.2	479
$3\pi^{0}$		$(1.54 \pm 0.26) \times 10^{-3}$		430
$\mu^{+}\mu^{-}\gamma$		$(1.03 \pm 0.26) \times 10^{-4}$		467
$\pi^{+}\pi^{-}\pi^{0}$		< 5 %	CL=90%	427
$\pi^{0}\rho^{0}$		< 4 %	CL=90%	118
$\pi^{+}\pi^{+}\pi^{-}\pi^{-}$		< 1 %	CL=90%	372
$\pi^{+}\pi^{+}\pi^{-}\pi^{-}$ neutrals		< 1 %	CL=95%	–
$\pi^{+}\pi^{+}\pi^{-}\pi^{-}\pi^{0}$		< 1 %	CL=90%	298
6π		< 1 %	CL=90%	189
$\pi^{+}\pi^{-}e^{+}e^{-}$		$< 6 \times 10^{-3}$	CL=90%	458
$\pi^{0}\gamma\gamma$		$< 8 \times 10^{-4}$	CL=90%	469
$4\pi^{0}$		$< 5 \times 10^{-4}$	CL=90%	379
$e^{+}e^{-}$		$< 2.1 \times 10^{-7}$	CL=90%	479
Charge conjugation (C) or Parity (P) violating modes				
$\pi^{+}\pi^{-}$	P,CP	< 2 %	CL=90%	458
$\pi^{0}\pi^{0}$	P,CP	$< 9 \times 10^{-4}$	CL=90%	459
$\pi^{0}e^{+}e^{-}$	C	[g] < 1.3 %	CL=90%	469
$\eta e^{+}e^{-}$	C	[g] < 1.1 %	CL=90%	322
3γ	C	$< 1.0 \times 10^{-4}$	CL=90%	479
$\mu^{+}\mu^{-}\pi^{0}$	C	[g] $< 6.0 \times 10^{-5}$	CL=90%	445
$\mu^{+}\mu^{-}\eta$	C	[g] $< 1.5 \times 10^{-5}$	CL=90%	274

$f_0(980)$ [k]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 980 \pm 10$ MeV
Full width $\Gamma = 40$ to 100 MeV

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi\pi$	dominant		470
$K\overline{K}$	seen		–
$\gamma\gamma$	$(1.19 \pm 0.33) \times 10^{-5}$		490
$e^{+}e^{-}$	$< 3 \times 10^{-7}$	90%	490

$a_0(980)$ [k]

$I^G(J^{PC}) = 1^-(0^{++})$

Mass $m = 983.4 \pm 0.9$ MeV
Full width $\Gamma = 50$ to 100 MeV

$a_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	dominant	321
$K\overline{K}$	seen	–
$\gamma\gamma$	seen	492

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.413 \pm 0.008$ MeV
Full width $\Gamma = 4.43 \pm 0.05$ MeV

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K^{+}K^{-}$	(49.1 ± 0.8) %	S=1.3	127
$K^{0}_{L}K^{0}_{S}$	(34.1 ± 0.6) %	S=1.2	110
$\rho\pi + \pi^{+}\pi^{-}\pi^{0}$	(15.5 ± 0.7) %	S=1.5	–
$\eta\gamma$	(1.26 ± 0.06) %	S=1.1	363
$\pi^{0}\gamma$	$(1.31 \pm 0.13) \times 10^{-3}$		501
$e^{+}e^{-}$	$(2.99 \pm 0.08) \times 10^{-4}$	S=1.2	510
$\mu^{+}\mu^{-}$	$(2.5 \pm 0.4) \times 10^{-4}$		499
$\eta e^{+}e^{-}$	$(1.3 ^{+0.8}_{-0.6}) \times 10^{-4}$		363
$\pi^{+}\pi^{-}$	$(8 ^{+5}_{-4}) \times 10^{-5}$	S=1.5	490
$\omega\gamma$	< 5 %	CL=84%	210
$\rho\gamma$	$< 7 \times 10^{-4}$	CL=90%	219
$\pi^{+}\pi^{-}\gamma$	$< 3 \times 10^{-5}$	CL=90%	490
$f_0(980)\gamma$	$< 1 \times 10^{-4}$	CL=90%	39
$\pi^{0}\pi^{0}\gamma$	$< 1 \times 10^{-3}$	CL=90%	492
$\pi^{+}\pi^{-}\pi^{+}\pi^{-}$	$< 8.7 \times 10^{-4}$	CL=90%	410
$\pi^{+}\pi^{+}\pi^{-}\pi^{-}\pi^{0}$	$< 1.5 \times 10^{-4}$	CL=95%	341
$\pi^{0}e^{+}e^{-}$	$< 1.2 \times 10^{-4}$	CL=90%	501
$\pi^{0}\eta\gamma$	$< 2.5 \times 10^{-3}$	CL=90%	346
$a_0(980)\gamma$	$< 5 \times 10^{-3}$	CL=90%	36
$\eta'(958)\gamma$	$(1.2 ^{+0.7}_{-0.5}) \times 10^{-4}$		–
$\mu^{+}\mu^{-}\gamma$	$(2.3 \pm 1.0) \times 10^{-5}$		–

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1170 \pm 20$ MeV
Full width $\Gamma = 360 \pm 40$ MeV

$h_1(1170)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	310

$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\omega\pi$	dominant		348
[D/S amplitude ratio $= 0.29 \pm 0.04$]			
$\pi^\pm\gamma$	$(1.6\pm0.4) \times 10^{-3}$		608
$\eta\rho$	seen		–
$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%	536
$(K\overline{K})^\pm\pi^0$	< 8 %	90%	248
$K_S^0 K_L^0 \pi^\pm$	< 6 %	90%	238
$K_S^0 K_S^0 \pi^\pm$	< 2 %	90%	238
$\phi\pi$	< 1.5 %	84%	146

$a_1(1260)$ [l]

$I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [m]
Full width $\Gamma = 250$ to 600 MeV

$a_1(1260)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	dominant	356
[D/S amplitude ratio $= -0.100 \pm 0.028$]		
$\pi\gamma$	seen	607
$\pi(\pi\pi)_{S\text{-wave}}$	possibly seen	575

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1275.0 \pm 1.2$ MeV
Full width $\Gamma = 185.5^{+3.8}_{-2.7}$ MeV (S = 1.5)

$f_2(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	$(84.6\ ^{+2.5}_{-1.3})$ %	S=1.3	622
$\pi^+\pi^-2\pi^0$	$(7.2\ ^{+1.5}_{-2.7})$ %	S=1.3	562
$K\overline{K}$	(4.6 ± 0.4) %	S=2.8	403
$2\pi^+2\pi^-$	(2.8 ± 0.4) %	S=1.2	559
$\eta\eta$	$(4.5 \pm 1.0) \times 10^{-3}$	S=2.4	327
$4\pi^0$	$(3.0 \pm 1.0) \times 10^{-3}$		564
$\gamma\gamma$	$(1.32^{+0.17}_{-0.16}) \times 10^{-5}$		637
$\eta\pi\pi$	$< 8 \times 10^{-3}$	CL=95%	475
$K^0 K^- \pi^+ +$ c.c.	$< 3.4 \times 10^{-3}$	CL=95%	293
e^+e^-	$< 9 \times 10^{-9}$	CL=90%	637

$f_1(1285)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1281.9 \pm 0.6$ MeV (S = 1.7)
Full width $\Gamma = 24.0 \pm 1.2$ MeV (S = 1.4)

$(4\pi = \rho(\pi\pi)_{Pwave})$

$f_1(1285)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
4π	(35 ± 4) %	S=1.6	563
$\pi^0\pi^0\pi^+\pi^-$	(23.5 ± 3.0) %	S=1.6	566
$2\pi^+2\pi^-$	(11.7 ± 1.5) %	S=1.6	563
$\rho^0\pi^+\pi^-$	(11.7 ± 1.5) %	S=1.6	340
$4\pi^0$	$< 7 \times 10^{-4}$	CL=90%	568
$\eta\pi\pi$	(50 ± 18) %		479
$a_0(980)\pi$ [ignoring $a_0(980) \to K\overline{K}$]	(34 ± 8) %	S=1.2	234
$\eta\pi\pi$ [excluding $a_0(980)\pi$]	(15 ± 7) %	S=1.1	–
$K\overline{K}\pi$	(9.6 ± 1.2) %	S=1.5	308
$K\overline{K}^*(892)$	not seen		–
$\gamma\rho^0$	(5.4 ± 1.2) %	S=2.3	410
$\phi\gamma$	$(7.9 \pm 3.0) \times 10^{-4}$		236

$\eta(1295)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 1297.0 \pm 2.8$ MeV
Full width $\Gamma = 53 \pm 6$ MeV

$\eta(1295)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi^+\pi^-$	seen	488
$a_0(980)\pi$	seen	245
$\eta\pi^0\pi^0$	seen	–
$\eta(\pi\pi)_{S\text{-wave}}$	seen	–

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 1300 \pm 100$ MeV [m]
Full width $\Gamma = 200$ to 600 MeV

$\pi(1300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	406
$\pi(\pi\pi)_{S\text{-wave}}$	seen	–

$a_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1318.1 \pm 0.6$ MeV (S = 1.1)
Full width $\Gamma = 107 \pm 5$ MeV [m] ($K^\pm K_S^0$ and $\eta\pi$ modes)

$a_2(1320)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\rho\pi$	(70.1 ± 2.7) %	S=1.2	419
$\eta\pi$	(14.5 ± 1.2) %		535
$\omega\pi\pi$	(10.6 ± 3.2) %	S=1.3	362
$K\overline{K}$	(4.9 ± 0.8) %		437
$\eta'(958)\pi$	$(5.3 \pm 0.9) \times 10^{-3}$		287
$\pi^\pm\gamma$	$(2.8 \pm 0.6) \times 10^{-3}$		652
$\gamma\gamma$	$(9.4 \pm 0.7) \times 10^{-6}$		659
$\pi^+\pi^-\pi^-$	< 8 %	CL=90%	621
e^+e^-	$< 2.3 \times 10^{-7}$	CL=90%	659

$f_0(1370)$ [k]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 1200$ to 1500 MeV
Full width $\Gamma = 200$ to 500 MeV

$f_0(1370)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	–
4π	seen	–
$4\pi^0$	seen	–
$2\pi^+2\pi^-$	seen	–
$\pi^+\pi^-2\pi^0$	seen	–
$2(\pi\pi)_{S\text{-wave}}$	seen	–
$\eta\eta$	seen	–
$K\overline{K}$	seen	–
$\gamma\gamma$	seen	–
e^+e^-	not seen	–

$f_1(1420)$ [n]

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1426.2 \pm 1.2$ MeV (S = 1.3)
Full width $\Gamma = 55.0 \pm 3.0$ MeV

$f_1(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	dominant	439
$K\overline{K}^*(892) +$ c.c.	dominant	155
$\eta\pi\pi$	possibly seen	571

$\omega(1420)$ [o]

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1419 \pm 31$ MeV
Full width $\Gamma = 174 \pm 60$ MeV

$\omega(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	dominant	488

$\eta(1440)$ [p]

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass m = 1400 - 1470 MeV [m]
Full width Γ = 50 - 80 MeV [m]

$\eta(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	seen	–
$K\overline{K}^*(892)$+ c.c.	seen	–
$\eta\pi\pi$	seen	–
$a_0(980)\pi$	seen	–
$\eta(\pi\pi)_{S\text{-wave}}$	seen	–
4π	seen	–

$a_0(1450)$

$I^G(J^{PC}) = 1^-(0^{++})$

Mass m = 1474 ± 19 MeV
Full width Γ = 265 ± 13 MeV

$a_0(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\eta$	seen	613
$\pi\eta'(958)$	seen	392
$K\overline{K}$	seen	530

$\rho(1450)$ [q]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass m = 1465 ± 25 MeV [m]
Full width Γ = 310 ± 60 MeV [m]

$\rho(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi\pi$	seen		719
4π	seen		665
$\omega\pi$	<2.0 %	95%	512
e^+e^-	seen		732
$\eta\rho$	<4 %		317
$\phi\pi$	<1 %		358
$K\overline{K}$	$<1.6 \times 10^{-3}$	95%	541

$f_0(1500)$ [r]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass m = 1500 ± 10 MeV (S = 1.3)
Full width Γ = 112 ± 10 MeV

$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\eta'(958)$	seen	–
$\eta\eta$	seen	513
4π	seen	–
$4\pi^0$	seen	690
$2\pi^+2\pi^-$	seen	686
2π	seen	–
$\pi^+\pi^-$	seen	737
$2\pi^0$	seen	738
$K\overline{K}$	seen	563

$f_2'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass m = 1525 ± 5 MeV [m]
Full width Γ = 76 ± 10 MeV [m]

$f_2'(1525)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	(88.8 ±3.1) %	581
$\eta\eta$	(10.3 ±3.1) %	531
$\pi\pi$	$(8.2 \pm 1.5) \times 10^{-3}$	750
$\gamma\gamma$	$(1.32 \pm 0.21) \times 10^{-6}$	763

$\omega(1600)$ [s]

$I^G(J^{PC}) = 0^-(1^{--})$

Mass m = 1649 ± 24 MeV (S = 2.3)
Full width Γ = 220 ± 35 MeV (S = 1.6)

$\omega(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	637
$\omega\pi\pi$	seen	601
e^+e^-	seen	824

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

Mass m = 1667 ± 4 MeV
Full width Γ = 168 ± 10 MeV [m]

$\omega_3(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	647
$\omega\pi\pi$	seen	614
$b_1(1235)\pi$	possibly seen	359

$\pi_2(1670)$

$I^G(J^{PC}) = 1^-(2^{-+})$

Mass m = 1670 ± 20 MeV [m]
Full width Γ = 258 ± 18 MeV [m] (S = 1.7)

$\pi_2(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
3π	(95.8±1.4) %	806
$f_2(1270)\pi$	(56.2±3.2) %	325
$\rho\pi$	(31 ±4) %	649
$f_0(1370)\pi$	(8.7±3.4) %	–
$K\overline{K}^*(892)$+ c.c.	(4.2±1.4) %	453

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass m = 1680 ± 20 MeV [m]
Full width Γ = 150 ± 50 MeV [m]

$\phi(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)$+ c.c.	dominant	463
$K_S^0K\pi$	seen	620
$K\overline{K}$	seen	681
e^+e^-	seen	840
$\omega\pi\pi$	not seen	622

$\rho_3(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

J^P from the 2π and $K\overline{K}$ modes.
Mass m = 1691 ± 5 MeV [m]
Full width Γ = 160 ± 10 MeV [m] (S = 1.5)

$\rho_3(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
4π	(71.1 ± 1.9) %		788
$\pi^\pm\pi^+\pi^-\pi^0$	(67 ±22) %		788
$\omega\pi$	(16 ± 6) %		656
$\pi\pi$	(23.6 ± 1.3) %		834
$K\overline{K}\pi$	(3.8 ± 1.2) %		628
$K\overline{K}$	(1.58± 0.26) %	1.2	686
$\eta\pi^+\pi^-$	seen		728

$\rho(1700)$ [q]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1700 \pm 20$ MeV [m] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)
Full width $\Gamma = 240 \pm 60$ MeV [m] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi\pi$	dominant	640
$2(\pi^+\pi^-)$	large	792
$\rho^0\pi^+\pi^-$	large	640
$\rho^\pm\pi^\mp\pi^0$	large	642
$\pi^+\pi^-$	seen	838
$\pi^-\pi^0$	seen	839
$K\overline{K}^*(892)+$ c.c.	seen	479
$\eta\rho$	seen	533
$K\overline{K}$	seen	692
e^+e^-	seen	850
$\pi^0\omega$	seen	662

$f_J(1710)$ [t]

$I^G(J^{PC}) = 0^+(\text{even}^{++})$

Mass $m = 1712 \pm 5$ MeV (S = 1.1)
Full width $\Gamma = 133 \pm 14$ MeV (S = 1.2)

$f_J(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	690
$\eta\eta$	seen	648
$\pi\pi$	seen	837

$\pi(1800)$

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 1801 \pm 13$ MeV (S = 1.9)
Full width $\Gamma = 210 \pm 15$ MeV

$\pi(1800)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^-\pi^-$	seen	–
$f_0(980)\pi^-$	seen	623
$f_0(1370)\pi^-$	seen	–
$\rho\pi^-$	not seen	728
$\eta\eta\pi^-$	seen	–
$a_0(980)\eta$	seen	459
$f_0(1500)\pi^-$	seen	240
$\eta\eta'(958)\pi^-$	seen	–
$K_0^*(1430)K^-$	seen	–
$K^*(892)K^-$	not seen	560

$\phi_3(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

Mass $m = 1854 \pm 7$ MeV
Full width $\Gamma = 87^{+28}_{-23}$ MeV (S = 1.2)

$\phi_3(1850)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	785
$K\overline{K}^*(892)+$ c.c.	seen	602

$f_2(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

Seen by one group only.
Mass $m = 2011^{+60}_{-80}$ MeV
Full width $\Gamma = 202 \pm 60$ MeV

$f_2(2010)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	–

$a_4(2040)$

$I^G(J^{PC}) = 1^-(4^{++})$

Mass $m = 2020 \pm 16$ MeV
Full width $\Gamma = 387 \pm 70$ MeV

$a_4(2040)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	892
$\pi^+\pi^-\pi^0$	seen	–
$\eta\pi^0$	seen	941

$f_4(2050)$

$I^G(J^{PC}) = 0^+(4^{++})$

Mass $m = 2044 \pm 11$ MeV (S = 1.4)
Full width $\Gamma = 208 \pm 13$ MeV (S = 1.2)

$f_4(2050)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\omega\omega$	(26 ± 6) %	658
$\pi\pi$	(17.0 ± 1.5) %	1012
$K\overline{K}$	$(6.8^{+3.4}_{-1.8}) \times 10^{-3}$	895
$\eta\eta$	$(2.1 \pm 0.8) \times 10^{-3}$	863
$4\pi^0$	< 1.2 %	977

$f_2(2300)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2297 \pm 28$ MeV
Full width $\Gamma = 149 \pm 40$ MeV

$f_2(2300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	529

$f_2(2340)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2339 \pm 60$ MeV
Full width $\Gamma = 319^{+80}_{-70}$ MeV

$f_2(2340)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	573

STRANGE MESONS ($S = \pm 1$, $C = B = 0$)

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [u] (S = 2.8)
Mean life $\tau = (1.2386 \pm 0.0024) \times 10^{-8}$ s (S = 2.0)
$c\tau = 3.713$ m

Slope parameter g [v]

(See Particle Listings for quadratic coefficients)

$K^+ \to \pi^+\pi^+\pi^- = -0.2154 \pm 0.0035$ (S = 1.4)
$K^- \to \pi^-\pi^-\pi^+ = -0.217 \pm 0.007$ (S = 2.5)
$K^\pm \to \pi^\pm\pi^0\pi^0 = 0.594 \pm 0.019$ (S = 1.3)

$K^\pm$ decay form factors [a,w]

K^+_{e3} $\lambda_+ = 0.0286 \pm 0.0022$
$K^+_{\mu 3}$ $\lambda_+ = 0.032 \pm 0.008$ (S = 1.6)
$K^+_{\mu 3}$ $\lambda_0 = 0.006 \pm 0.007$ (S = 1.6)
K^+_{e3} $|f_S/f_+| = 0.084 \pm 0.023$ (S = 1.2)
K^+_{e3} $|f_T/f_+| = 0.38 \pm 0.11$ (S = 1.1)
$K^+_{\mu 3}$ $|f_T/f_+| = 0.02 \pm 0.12$
$K^+ \to e^+\nu_e\gamma$ $|F_A + F_V| = 0.148 \pm 0.010$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A + F_V| < 0.23$, CL = 90%
$K^+ \to e^+\nu_e\gamma$ $|F_A - F_V| < 0.49$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A - F_V| = -2.2$ to 0.3

K^- modes are charge conjugates of the modes below.

K^+ DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\mu^+\nu_\mu$			(63.51 ± 0.18) %	S=1.3	236
$e^+\nu_e$			$(1.55 \pm 0.07) \times 10^{-5}$		247
$\pi^+\pi^0$			(21.16 ± 0.14) %	S=1.1	205
$\pi^+\pi^+\pi^-$			(5.59 ± 0.05) %	S=1.8	125
$\pi^+\pi^0\pi^0$			(1.73 ± 0.04) %	S=1.2	133
$\pi^0\mu^+\nu_\mu$			(3.18 ± 0.08) %	S=1.5	215
Called $K^+_{\mu 3}$.					
$\pi^0 e^+\nu_e$			(4.82 ± 0.06) %	S=1.3	228
Called K^+_{e3}.					
$\pi^0\pi^0 e^+\nu_e$			$(2.1 \pm 0.4) \times 10^{-5}$		206
$\pi^+\pi^- e^+\nu_e$			$(3.91 \pm 0.17) \times 10^{-5}$		203
$\pi^+\pi^-\mu^+\nu_\mu$			$(1.4 \pm 0.9) \times 10^{-5}$		151
$\pi^0\pi^0\pi^0 e^+\nu_e$			$< 3.5 \times 10^{-6}$	CL=90%	135
$\pi^+\gamma\gamma$		[x]	$(1.10 \pm 0.32) \times 10^{-6}$		227
$\pi^+ 3\gamma$		[x]	$< 1.0 \times 10^{-4}$	CL=90%	227
$\mu^+\nu_\mu\nu\overline{\nu}$			$< 6.0 \times 10^{-6}$	CL=90%	236
$e^+\nu_e\nu\overline{\nu}$			$< 6 \times 10^{-5}$	CL=90%	247
$\mu^+\nu_\mu e^+ e^-$			$(1.3 \pm 0.4) \times 10^{-7}$		236
$e^+\nu_e e^+ e^-$			$(3.0\,^{+3.0}_{-1.5}) \times 10^{-8}$		247
$\mu^+\nu_\mu\mu^+\mu^-$			$< 4.1 \times 10^{-7}$	CL=90%	185
$\mu^+\nu_\mu\gamma$		[x,y]	$(5.50 \pm 0.28) \times 10^{-3}$		236
$\pi^+\pi^0\gamma$		[x,y]	$(2.75 \pm 0.15) \times 10^{-4}$		205
$\pi^+\pi^0\gamma$(DE)		[x,z]	$(1.8 \pm 0.4) \times 10^{-5}$		205
$\pi^+\pi^+\pi^-\gamma$		[x,y]	$(1.04 \pm 0.31) \times 10^{-4}$		125
$\pi^+\pi^0\pi^0\gamma$		[x,y]	$(7.5\,^{+5.5}_{-3.0}) \times 10^{-6}$		133
$\pi^0\mu^+\nu_\mu\gamma$		[x,y]	$< 6.1 \times 10^{-5}$	CL=90%	215
$\pi^0 e^+\nu_e\gamma$		[x,y]	$(2.62 \pm 0.20) \times 10^{-4}$		228
$\pi^0 e^+\nu_e\gamma$(SD)		[aa]	$< 5.3 \times 10^{-5}$	CL=90%	228
$\pi^0\pi^0 e^+\nu_e\gamma$			$< 5 \times 10^{-6}$	CL=90%	206
Lepton Family number (LF), Lepton number (L), $\Delta S = \Delta Q$ (SQ) violating modes, or $\Delta S = 1$ weak neutral current ($S1$) modes					
$\pi^+\pi^+ e^-\overline{\nu}_e$	SQ		$< 1.2 \times 10^{-8}$	CL=90%	203
$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	SQ		$< 3.0 \times 10^{-6}$	CL=95%	151
$\pi^+ e^+ e^-$	$S1$		$(2.74 \pm 0.23) \times 10^{-7}$		227
$\pi^+\mu^+\mu^-$	$S1$		$(5.0 \pm 1.0) \times 10^{-8}$		172
$\pi^+\nu\overline{\nu}$	$S1$		$(4.2\,^{+9.7}_{-3.5}) \times 10^{-10}$		227
$\mu^-\nu e^+ e^+$	LF		$< 2.0 \times 10^{-8}$	CL=90%	236
$\mu^+\nu_e$	LF	[d]	$< 4 \times 10^{-3}$	CL=90%	236
$\pi^+\mu^+ e^-$	LF		$< 2.1 \times 10^{-10}$	CL=90%	214
$\pi^+\mu^- e^+$	LF		$< 7 \times 10^{-9}$	CL=90%	214
$\pi^-\mu^+ e^+$	L		$< 7 \times 10^{-9}$	CL=90%	214
$\pi^- e^+ e^+$	L		$< 1.0 \times 10^{-8}$	CL=90%	227
$\pi^-\mu^+\mu^+$	L	[d]	$< 1.5 \times 10^{-4}$	CL=90%	172
$\mu^+\overline{\nu}_e$	L	[d]	$< 3.3 \times 10^{-3}$	CL=90%	236
$\pi^0 e^+\overline{\nu}_e$	L		$< 3 \times 10^{-3}$	CL=90%	228

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L

Mass $m = 497.672 \pm 0.031$ MeV
$m_{K^0} - m_{K^\pm} = 3.995 \pm 0.034$ MeV (S = 1.1)
$\left|m_{K^0} - m_{\overline{K}^0}\right| / m_{\text{average}} < 10^{-18}$ [bb]

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

Mean life $\tau = (0.8934 \pm 0.0008) \times 10^{-10}$ s
$c\tau = 2.6762$ cm

CP-violation parameters [cc]

$\text{Im}(\eta_{+-0}) = -0.002 \pm 0.008$
$\text{Im}(\eta_{000})^2 < 0.1$, CL = 90%

K^0_S DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-$			(68.61 ± 0.28) %	S=1.2	206
$\pi^0\pi^0$			(31.39 ± 0.28) %	S=1.2	209
$\pi^+\pi^-\gamma$		[y,dd]	$(1.78 \pm 0.05) \times 10^{-3}$		206
$\gamma\gamma$			$(2.4 \pm 0.9) \times 10^{-6}$		249
$\pi^+\pi^-\pi^0$			$(3.4\,^{+1.1}_{-0.9}) \times 10^{-7}$		133
$3\pi^0$			$< 3.7 \times 10^{-5}$	CL=90%	139
$\pi^\pm e^\mp\nu$		[ee]	$(6.70 \pm 0.07) \times 10^{-4}$	S=1.1	229
$\pi^\pm\mu^\mp\nu$		[ee]	$(4.69 \pm 0.06) \times 10^{-4}$	S=1.1	216
$\Delta S = 1$ weak neutral current ($S1$) modes					
$\mu^+\mu^-$	$S1$		$< 3.2 \times 10^{-7}$	CL=90%	225
$e^+ e^-$	$S1$		$< 1.4 \times 10^{-7}$	CL=90%	249
$\pi^0 e^+ e^-$	$S1$		$< 1.1 \times 10^{-6}$	CL=90%	231

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K_L} - m_{K_S} = (0.5301 \pm 0.0014) \times 10^{10}\ \hbar\ \text{s}^{-1}$
$= (3.489 \pm 0.009) \times 10^{-12}$ MeV
Mean life $\tau = (5.17 \pm 0.04) \times 10^{-8}$ s (S = 1.1)
$c\tau = 15.51$ m

Slope parameter g [v]

(See Particle Listings for quadratic coefficients)

$K^0_L \to \pi^+\pi^-\pi^0 = 0.670 \pm 0.014$ (S = 1.6)

K_L decay form factors [w]

K^0_{e3} $\lambda_+ = 0.0300 \pm 0.0016$ (S = 1.2)
$K^0_{\mu 3}$ $\lambda_+ = 0.034 \pm 0.005$ (S = 2.3)
$K^0_{\mu 3}$ $\lambda_0 = 0.025 \pm 0.006$ (S = 2.3)
K^0_{e3} $|f_S/f_+| < 0.04$, CL = 68%
K^0_{e3} $|f_T/f_+| < 0.23$, CL = 68%
$K^0_{\mu 3}$ $|f_T/f_+| = 0.12 \pm 0.12$
$K_L \to e^+e^-\gamma$: $\alpha_{K^*} = -0.28 \pm 0.08$

CP-violation parameters [cc]

$\delta = (0.327 \pm 0.012)\%$

$|\eta_{00}| = (2.275 \pm 0.019) \times 10^{-3}$ (S = 1.1)

$|\eta_{+-}| = (2.285 \pm 0.019) \times 10^{-3}$

$|\eta_{00}/\eta_{+-}| = 0.9956 \pm 0.0023$ [ff] (S = 1.8)

$\epsilon'/\epsilon = (1.5 \pm 0.8) \times 10^{-3}$ [ff] (S = 1.8)

$\phi_{+-} = (43.5 \pm 0.6)^\circ$

$\phi_{00} = (43.4 \pm 1.0)^\circ$

$\phi_{00} - \phi_{+-} = (-0.1 \pm 0.8)^\circ$

j for $K^0_L \to \pi^+\pi^-\pi^0 = 0.0011 \pm 0.0008$

$|\eta_{+-\gamma}| = (2.35 \pm 0.07) \times 10^{-3}$

$\phi_{+-\gamma} = (44 \pm 4)^\circ$

$|\epsilon'_{+-\gamma}|/\epsilon < 0.3$, CL = 90%

$\Delta S = -\Delta Q$ in $K^0_{\ell 3}$ decay

Re $x = 0.006 \pm 0.018$ (S = 1.3)

Im $x = -0.003 \pm 0.026$ (S = 1.2)

CPT-violation parameters

Re $\Delta = 0.018 \pm 0.020$

Im $\Delta = 0.02 \pm 0.04$

K^0_L DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$3\pi^0$		$(21.12 \pm 0.27)\ \%$	S=1.1	139
$\pi^+\pi^-\pi^0$		$(12.56 \pm 0.20)\ \%$	S=1.7	133
$\pi^\pm\mu^\mp\nu$	[gg]	$(27.17 \pm 0.25)\ \%$	S=1.1	216
Called $K^0_{\mu3}$.				
$\pi^\pm e^\mp\nu_e$	[gg]	$(38.78 \pm 0.27)\ \%$	S=1.1	229
Called K^0_{e3}.				
2γ		$(5.92 \pm 0.15) \times 10^{-4}$		249
3γ		$< 2.4 \times 10^{-7}$	CL=90%	249
$\pi^0 2\gamma$	[hh]	$(1.70 \pm 0.28) \times 10^{-6}$		231
$\pi^0\pi^\pm e^\mp\nu$	[gg]	$(5.18 \pm 0.29) \times 10^{-5}$		207
$(\pi\mu\text{atom})\nu$		$(1.06 \pm 0.11) \times 10^{-7}$		–
$\pi^\pm e^\mp\nu_e\gamma$	[y,gg,hh]	$(3.62 {}^{+0.26}_{-0.21}) \times 10^{-3}$		229
$\pi^+\pi^-\gamma$	[y,hh]	$(4.61 \pm 0.14) \times 10^{-5}$		206
$\pi^0\pi^0\gamma$		$< 5.6 \times 10^{-6}$		209

Charge conjugation × Parity (CP, CPV) or Lepton Family number (LF) violating modes, or $\Delta S = 1$ weak neutral current ($S1$) modes

$\pi^+\pi^-$	CPV		$(2.067 \pm 0.035) \times 10^{-3}$	S=1.1	206
$\pi^0\pi^0$	CPV		$(9.36 \pm 0.20) \times 10^{-4}$		209
$\mu^+\mu^-$	$S1$		$(7.2 \pm 0.5) \times 10^{-9}$	S=1.4	225
$\mu^+\mu^-\gamma$	$S1$		$(3.25 \pm 0.28) \times 10^{-7}$		225
e^+e^-	$S1$		$< 4.1 \times 10^{-11}$	CL=90%	249
$e^+e^-\gamma$	$S1$		$(9.1 \pm 0.5) \times 10^{-6}$		249
$e^+e^-\gamma\gamma$	$S1$	[hh]	$(6.5 \pm 1.2) \times 10^{-7}$		249
$\pi^+\pi^-e^+e^-$	$S1$	[hh]	$< 4.6 \times 10^{-7}$	CL=90%	206
$\mu^+\mu^-e^+e^-$	$S1$		$(2.9 {}^{+6.7}_{-2.4}) \times 10^{-9}$		225
$e^+e^-e^+e^-$	$S1$		$(4.1 \pm 0.8) \times 10^{-8}$	S=1.2	249
$\pi^0\mu^+\mu^-$	CP,$S1$	[ii]	$< 5.1 \times 10^{-9}$	CL=90%	177
$\pi^0e^+e^-$	CP,$S1$	[ii]	$< 4.3 \times 10^{-9}$	CL=90%	231
$\pi^0\nu\overline{\nu}$	CP,$S1$	[jj]	$< 5.8 \times 10^{-5}$	CL=90%	231
$e^\pm\mu^\mp$	LF	[gg]	$< 3.3 \times 10^{-11}$	CL=90%	238
$e^\pm e^\pm\mu^\mp\mu^\mp$	LF	[gg]	$< 6.1 \times 10^{-9}$	CL=90%	–

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)^\pm$ mass $m = 891.66 \pm 0.26$ MeV

$K^*(892)^0$ mass $m = 896.10 \pm 0.28$ MeV (S = 1.4)

$K^*(892)^\pm$ full width $\Gamma = 50.8 \pm 0.9$ MeV

$K^*(892)^0$ full width $\Gamma = 50.5 \pm 0.6$ MeV (S = 1.1)

$K^*(892)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K\pi$	$\sim 100\ \%$		291
$K^0\gamma$	$(2.30 \pm 0.20) \times 10^{-3}$		310
$K^\pm\gamma$	$(9.9 \pm 0.9) \times 10^{-4}$		309
$K\pi\pi$	$< 7 \times 10^{-4}$	95%	224

$K_1(1270)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1273 \pm 7$ MeV [m]

Full width $\Gamma = 90 \pm 20$ MeV [m]

$K_1(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\rho$	$(42 \pm 6)\ \%$	76
$K^*_0(1430)\pi$	$(28 \pm 4)\ \%$	–
$K^*(892)\pi$	$(16 \pm 5)\ \%$	301
$K\omega$	$(11.0 \pm 2.0)\ \%$	–
$K f_0(1370)$	$(3.0 \pm 2.0)\ \%$	–

$K_1(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1402 \pm 7$ MeV

Full width $\Gamma = 174 \pm 13$ MeV (S = 1.6)

$K_1(1400)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K^*(892)\pi$	$(94 \pm 6)\ \%$	401
$K\rho$	$(3.0 \pm 3.0)\ \%$	298
$K f_0(1370)$	$(2.0 \pm 2.0)\ \%$	–
$K\omega$	$(1.0 \pm 1.0)\ \%$	285
$K^*_0(1430)\pi$	not seen	–

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1414 \pm 15$ MeV (S = 1.3)

Full width $\Gamma = 232 \pm 21$ MeV (S = 1.1)

$K^*(1410)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^*(892)\pi$	$> 40\ \%$	95%	408
$K\pi$	$(6.6 \pm 1.3)\ \%$		611
$K\rho$	$< 7\ \%$	95%	309

$K^*_0(1430)$ [kk]

$I(J^P) = \frac{1}{2}(0^+)$

Mass $m = 1429 \pm 6$ MeV

Full width $\Gamma = 287 \pm 23$ MeV

$K^*_0(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	$(93 \pm 10)\ \%$	621

$K^*_2(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

$K^*_2(1430)^\pm$ mass $m = 1425.6 \pm 1.5$ MeV (S = 1.1)

$K^*_2(1430)^0$ mass $m = 1432.4 \pm 1.3$ MeV

$K^*_2(1430)^\pm$ full width $\Gamma = 98.5 \pm 2.7$ MeV (S = 1.1)

$K^*_2(1430)^0$ full width $\Gamma = 109 \pm 5$ MeV (S = 1.9)

$K^*_2(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K\pi$	$(49.9 \pm 1.2)\ \%$		622
$K^*(892)\pi$	$(24.7 \pm 1.5)\ \%$		423
$K^*(892)\pi\pi$	$(13.4 \pm 2.2)\ \%$		375
$K\rho$	$(8.7 \pm 0.8)\ \%$	S=1.2	331
$K\omega$	$(2.9 \pm 0.8)\ \%$		319
$K^+\gamma$	$(2.4 \pm 0.5) \times 10^{-3}$	S=1.1	627
$K\eta$	$(1.5 {}^{+3.4}_{-1.0}) \times 10^{-3}$	S=1.3	492
$K\omega\pi$	$< 7.2 \times 10^{-4}$	CL=95%	110
$K^0\gamma$	$< 9 \times 10^{-4}$	CL=90%	631

$K^*(1680)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1717 \pm 27$ MeV (S = 1.4)
Full width $\Gamma = 322 \pm 110$ MeV (S = 4.2)

$K^*(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(38.7 ± 2.5) %	779
$K\rho$	$(31.4^{+4.7}_{-2.1})$ %	571
$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %	615

$K_2(1770)$ [ll]

$I(J^P) = \frac{1}{2}(2^-)$

Mass $m = 1773 \pm 8$ MeV
Full width $\Gamma = 186 \pm 14$ MeV

$K_2(1770)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi\pi$		–
$K_2^*(1430)\pi$	dominant	287
$K^*(892)\pi$	seen	653
$K f_2(1270)$	seen	–
$K\phi$	seen	441
$K\omega$	seen	608

$K_3^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

Mass $m = 1776 \pm 7$ MeV (S = 1.1)
Full width $\Gamma = 159 \pm 21$ MeV (S = 1.3)

$K_3^*(1780)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K\rho$	(31 ± 9) %		612
$K^*(892)\pi$	(20 ± 5) %		651
$K\pi$	(18.8 ± 1.0) %		810
$K\eta$	(30 ± 13) %		715
$K_2^*(1430)\pi$	< 16 %	95%	284

$K_2(1820)$ [mm]

$I(J^P) = \frac{1}{2}(2^-)$

Mass $m = 1816 \pm 13$ MeV
Full width $\Gamma = 276 \pm 35$ MeV

$K_2(1820)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K_2^*(1430)\pi$	seen	325
$K^*(892)\pi$	seen	680
$K f_2(1270)$	seen	186
$K\omega$	seen	638

$K_4^*(2045)$

$I(J^P) = \frac{1}{2}(4^+)$

Mass $m = 2045 \pm 9$ MeV (S = 1.1)
Full width $\Gamma = 198 \pm 30$ MeV

$K_4^*(2045)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(9.9 ± 1.2) %	958
$K^*(892)\pi\pi$	(9 ± 5) %	800
$K^*(892)\pi\pi\pi$	(7 ± 5) %	764
$\rho K\pi$	(5.7 ± 3.2) %	742
$\omega K\pi$	(5.0 ± 3.0) %	736
$\phi K\pi$	(2.8 ± 1.4) %	591
$\phi K^*(892)$	(1.4 ± 0.7) %	363

CHARMED MESONS
$(C = \pm 1)$

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}u$, $D^- = \overline{c}d$, similarly for D^*'s

$D^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.3 \pm 0.5$ MeV (S = 1.1)
Mean life $\tau = (1.057 \pm 0.015) \times 10^{-12}$ s
$c\tau = 317$ μm

CP-violation decay-rate asymmetries

$A_{CP}(K^+K^-\pi^\pm) = -0.017 \pm 0.027$
$A_{CP}(K^\pm K^{*0}) = -0.02 \pm 0.05$
$A_{CP}(\phi\pi^\pm) = -0.014 \pm 0.033$
$A_{CP}(\pi^+\pi^-\pi^\pm) = -0.02 \pm 0.04$

$D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$ form factors

$r_2 = 0.72 \pm 0.09$
$r_v = 1.85 \pm 0.12$
$\Gamma_L/\Gamma_T = 1.23 \pm 0.13$
$\Gamma_+/\Gamma_- = 0.16 \pm 0.04$

D^- modes are charge conjugates of the modes below.

D^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes				
e^+ anything		(17.2 ± 1.9) %		–
K^- anything		(24.2 ± 2.8) %	S=1.4	–
$\overline{K}^0$ anything + K^0 anything		(59 ± 7) %		–
K^+ anything		(5.8 ± 1.4) %		–
η anything	[nn]	< 13 %	CL=90%	–
Leptonic and semileptonic modes				
$\mu^+\nu_\mu$		$< 7.2 \times 10^{-4}$	CL=90%	932
$\overline{K}^0 \ell^+ \nu_\ell$	[oo]	(6.8 ± 0.8) %		868
$\overline{K}^0 e^+ \nu_e$		(6.7 ± 0.9) %		868
$\overline{K}^0 \mu^+ \nu_\mu$		$(7.0 ^{+3.0}_{-2.0})$ %		865
$K^-\pi^+ e^+ \nu_e$		$(4.1 ^{+0.9}_{-0.7})$ %		863
$\overline{K}^*(892)^0 e^+ \nu_e$		(3.2 ± 0.33) %		720
$\times$ B$(\overline{K}^{*0} \rightarrow K^-\pi^+)$				
$K^-\pi^+ e^+ \nu_e$ nonresonant		$< 7 \times 10^{-3}$	CL=90%	863
$K^-\pi^+ \mu^+ \nu_\mu$		(3.2 ± 0.4) %	S=1.1	851
$\overline{K}^*(892)^0 \mu^+ \nu_\mu$		(2.9 ± 0.4) %		715
$\times$ B$(\overline{K}^{*0} \rightarrow K^-\pi^+)$				
$K^-\pi^+ \mu^+ \nu_\mu$ nonresonant		$(2.7 \pm 1.1) \times 10^{-3}$		851
$(\overline{K}^*(892)\pi)^0 e^+ \nu_e$		< 1.2 %	CL=90%	714
$(\overline{K}\pi\pi)^0 e^+ \nu_e$ non-$\overline{K}^*(892)$		$< 9 \times 10^{-3}$	CL=90%	846
$K^-\pi^+\pi^0 \mu^+ \nu_\mu$		$< 1.4 \times 10^{-3}$	CL=90%	825
$\pi^0 \ell^+ \nu_\ell$	[pp]	$(3.1 \pm 1.5) \times 10^{-3}$		930

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\overline{K}^*(892)^0 \ell^+ \nu_\ell$	[oo]	(4.7 ± 0.4) %		720
$\overline{K}^*(892)^0 e^+ \nu_e$		(4.8 ± 0.5) %		720
$\overline{K}^*(892)^0 \mu^+ \nu_\mu$		(4.4 ± 0.6) %	S=1.1	715
$\rho^0 e^+ \nu_e$		$(2.2 \pm 0.8) \times 10^{-3}$		776
$\rho^0 \mu^+ \nu_\mu$		$(2.7 \pm 0.7) \times 10^{-3}$		772
$\phi e^+ \nu_e$		< 2.09 %	CL=90%	657
$\phi \mu^+ \nu_\mu$		< 3.72 %	CL=90%	651
$\eta \ell^+ \nu_\ell$		$< 5 \times 10^{-3}$	CL=90%	–
$\eta'(958) \mu^+ \nu_\mu$		$< 9 \times 10^{-3}$	CL=90%	684
Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$				
$\overline{K}^0 \pi^+$		(2.89 ± 0.26) %	S=1.1	862
$K^-\pi^+\pi^+$	[qq]	(9.0 ± 0.6) %		845
$\overline{K}^*(892)^0 \pi^+$		(1.27 ± 0.13) %		712
$\times$ B$(\overline{K}^{*0} \rightarrow K^-\pi^+)$				
$\overline{K}_0^*(1430)^0 \pi^+$		(2.3 ± 0.3) %		368
$\times$ B$(\overline{K}_0^*(1430)^0 \rightarrow K^-\pi^+)$				
$\overline{K}^*(1680)^0 \pi^+$		$(3.7 \pm 0.8) \times 10^{-3}$		65
$\times$ B$(\overline{K}^*(1680)^0 \rightarrow K^-\pi^+)$				
$K^-\pi^+\pi^+$ nonresonant		(8.5 ± 0.8) %		845
$\overline{K}^0 \pi^+ \pi^0$	[qq]	(9.7 ± 3.0) %	S=1.1	845

$\overline{K}^0\rho^+$		$(6.6 \pm 2.5)\%$		680
$\overline{K}^*(892)^0\pi^+ \times B(\overline{K}^{*0} \to \overline{K}^0\pi^0)$		$(6.3 \pm 0.4) \times 10^{-3}$		712
$\overline{K}^0\pi^+\pi^0$ nonresonant		$(1.3 \pm 1.1)\%$		845
$K^-\pi^+\pi^+\pi^0$	[qq]	$(6.4 \pm 1.1)\%$		816
$\overline{K}^*(892)^0\rho^+$ total $\times B(\overline{K}^{*0} \to K^-\pi^+)$		$(1.4 \pm 0.9)\%$		423
$\overline{K}_1(1400)^0\pi^+ \times B(\overline{K}_1(1400)^0 \to K^-\pi^+\pi^0)$		$(2.2 \pm 0.6)\%$		390
$K^-\rho^+\pi^+$ total		$(3.1 \pm 1.1)\%$		616
$K^-\rho^+\pi^+$ 3-body		$(1.1 \pm 0.4)\%$		616
$\overline{K}^*(892)^0\pi^+\pi^0$ total $\times B(\overline{K}^{*0} \to K^-\pi^+)$		$(4.5 \pm 0.9)\%$		687
$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body $\times B(\overline{K}^{*0} \to K^-\pi^+)$		$(2.8 \pm 0.9)\%$		687
$K^*(892)^-\pi^+\pi^+$ 3-body $\times B(K^{*-} \to K^-\pi^0)$		$(7 \pm 3) \times 10^{-3}$		688
$K^-\pi^+\pi^+\pi^0$ nonresonant	[rr]	$(1.2 \pm 0.6)\%$		816
$\overline{K}^0\pi^+\pi^+\pi^-$	[qq]	$(7.0 \pm 0.9)\%$		814
$\overline{K}^0 a_1(1260)^+ \times B(a_1(1260)^+ \to \pi^+\pi^+\pi^-)$		$(4.0 \pm 0.9)\%$		328
$\overline{K}_1(1400)^0\pi^+ \times B(\overline{K}_1(1400)^0 \to \overline{K}^0\pi^+\pi^-)$		$(2.2 \pm 0.6)\%$		390
$K^*(892)^-\pi^+\pi^+$ 3-body $\times B(K^{*-} \to \overline{K}^0\pi^-)$		$(1.4 \pm 0.6)\%$		688
$\overline{K}^0\rho^0\pi^+$ total		$(4.2 \pm 0.9)\%$		614
$\overline{K}^0\rho^0\pi^+$ 3-body		$(5 \pm 5) \times 10^{-3}$		614
$\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant		$(8 \pm 4) \times 10^{-3}$		814
$K^-\pi^+\pi^+\pi^+\pi^-$	[qq]	$(7.2 \pm 1.0) \times 10^{-3}$		772
$\overline{K}^*(892)^0\pi^+\pi^+\pi^- \times B(\overline{K}^{*0} \to K^-\pi^+)$		$(5.4 \pm 2.3) \times 10^{-3}$		642
$\overline{K}^*(892)^0\rho^0\pi^+ \times B(\overline{K}^{*0} \to K^-\pi^+)$		$(1.9^{+1.1}_{-1.0}) \times 10^{-3}$		242
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$ no-ρ $\times B(\overline{K}^{*0} \to K^-\pi^+)$		$(2.9 \pm 1.1) \times 10^{-3}$		642
$K^-\rho^0\pi^+\pi^+$		$(3.1 \pm 0.9) \times 10^{-3}$		529
$K^-\pi^+\pi^+\pi^+\pi^-$ nonresonant		$< 2.3 \times 10^{-3}$	CL=90%	772
$K^-\pi^+\pi^+\pi^0\pi^0$		$(2.2^{+5.0}_{-0.9})\%$		775
$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$		$(5.4^{+3.0}_{-1.4})\%$		773
$\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-$		$(8 \pm 7) \times 10^{-4}$		714
$K^-\pi^+\pi^+\pi^+\pi^-\pi^0$		$(2.0 \pm 1.8) \times 10^{-3}$		718
$\overline{K}^0\overline{K}^0K^+$		$(1.8 \pm 0.8)\%$		545

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\overline{K}^0\rho^+$		$(6.6 \pm 2.5)\%$		680
$\overline{K}^0 a_1(1260)^+$		$(8.0 \pm 1.7)\%$		328
$\overline{K}^0 a_2(1320)^+$		$< 3 \times 10^{-3}$	CL=90%	199
$\overline{K}^*(892)^0\pi^+$		$(1.90 \pm 0.19)\%$		712
$\overline{K}^*(892)^0\rho^+$ total	[rr]	$(2.1 \pm 1.3)\%$		423
$\overline{K}^*(892)^0\rho^+$ S-wave	[rr]	$(1.6 \pm 1.6)\%$		423
$\overline{K}^*(892)^0\rho^+$ P-wave		$< 1 \times 10^{-3}$	CL=90%	423
$\overline{K}^*(892)^0\rho^+$ D-wave		$(10 \pm 7) \times 10^{-3}$		423
$\overline{K}^*(892)^0\rho^+$ D-wave longitudinal		$< 7 \times 10^{-3}$	CL=90%	423
$\overline{K}_1(1270)^0\pi^+$		$< 7 \times 10^{-3}$	CL=90%	487
$\overline{K}_1(1400)^0\pi^+$		$(4.9 \pm 1.2)\%$		390
$\overline{K}^*(1410)^0\pi^+$		$< 7 \times 10^{-3}$	CL=90%	382
$\overline{K}_0^*(1430)^0\pi^+$		$(3.7 \pm 0.4)\%$		368
$\overline{K}^*(1680)^0\pi^+$		$(1.43 \pm 0.30)\%$		65
$\overline{K}^*(892)^0\pi^+\pi^0$ total		$(6.7 \pm 1.4)\%$		687
$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body	[rr]	$(4.2 \pm 1.4)\%$		687
$K^*(892)^-\pi^+\pi^+$ 3-body		$(2.0 \pm 0.9)\%$		688
$K^-\rho^+\pi^+$ total		$(3.1 \pm 1.1)\%$		616
$K^-\rho^+\pi^+$ 3-body		$(1.1 \pm 0.4)\%$		616
$\overline{K}^0\rho^0\pi^+$ total		$(4.2 \pm 0.9)\%$	CL=90%	614
$\overline{K}^0\rho^0\pi^+$ 3-body		$(5 \pm 5) \times 10^{-3}$		614
$\overline{K}^0 f_0(980)\pi^+$		$< 5 \times 10^{-3}$	CL=90%	461
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$		$(8.1 \pm 3.4) \times 10^{-3}$	S=1.7	642
$\overline{K}^*(892)^0\rho^0\pi^+$		$(2.9^{+1.7}_{-1.5}) \times 10^{-3}$	S=1.8	242
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$ no-ρ		$(4.3 \pm 1.7) \times 10^{-3}$		642
$K^-\rho^0\pi^+\pi^+$		$(3.1 \pm 0.9) \times 10^{-3}$		529

Pionic modes

$\pi^+\pi^0$		$(2.5 \pm 0.7) \times 10^{-3}$		925
$\pi^+\pi^+\pi^-$		$(3.6 \pm 0.4) \times 10^{-3}$		908
$\rho^0\pi^+$		$(1.05 \pm 0.31) \times 10^{-3}$		769
$\pi^+\pi^+\pi^-$ nonresonant		$(2.2 \pm 0.4) \times 10^{-3}$		908
$\pi^+\pi^+\pi^-\pi^0$		$(1.9^{+1.5}_{-1.2})\%$		882
$\eta\pi^+ \times B(\eta \to \pi^+\pi^-\pi^0)$		$(1.7 \pm 0.6) \times 10^{-3}$		848
$\omega\pi^+ \times B(\omega \to \pi^+\pi^-\pi^0)$		$< 6 \times 10^{-3}$	CL=90%	764
$\pi^+\pi^+\pi^+\pi^-\pi^-$		$(2.1 \pm 0.4) \times 10^{-3}$		845
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		$(2.9^{+2.9}_{-2.0}) \times 10^{-3}$		799

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\eta\pi^+$		$(7.5 \pm 2.5) \times 10^{-3}$		848
$\rho^0\pi^+$		$(1.05 \pm 0.31) \times 10^{-3}$		769
$\omega\pi^+$		$< 7 \times 10^{-3}$	CL=90%	764
$\eta\rho^+$		$< 1.2\%$	CL=90%	658
$\eta'(958)\pi^+$		$< 9 \times 10^{-3}$	CL=90%	680
$\eta'(958)\rho^+$		$< 1.5\%$	CL=90%	355

Hadronic modes with a $K\overline{K}$ pair

$K^+\overline{K}^0$		$(7.4 \pm 1.0) \times 10^{-3}$		792
$K^+K^-\pi^+$	[qq]	$(8.8 \pm 0.8) \times 10^{-3}$		744
$\phi\pi^+ \times B(\phi \to K^+K^-)$		$(3.0 \pm 0.3) \times 10^{-3}$		647
$K^+\overline{K}^*(892)^0 \times B(\overline{K}^{*0} \to K^-\pi^+)$		$(2.8 \pm 0.4) \times 10^{-3}$		610
$K^+K^-\pi^+$ nonresonant		$(4.5 \pm 0.9) \times 10^{-3}$		744
$K^0\overline{K}^0\pi^+$		—		741
$K^*(892)^+\overline{K}^0 \times B(K^{*+} \to K^0\pi^+)$		$(2.1 \pm 1.0)\%$		611
$K^+K^-\pi^+\pi^0$		—		682
$\phi\pi^+\pi^0 \times B(\phi \to K^+K^-)$		$(1.1 \pm 0.5)\%$		619
$\phi\rho^+ \times B(\phi \to K^+K^-)$		$< 7 \times 10^{-3}$	CL=90%	268
$K^+K^-\pi^+\pi^0$ non-ϕ		$(1.5^{+0.7}_{-0.6})\%$		682
$K^+\overline{K}^0\pi^+\pi^-$		$< 2\%$	CL=90%	678
$K^0K^-\pi^+\pi^+$		$(1.0 \pm 0.6)\%$		678
$K^*(892)^+\overline{K}^*(892)^0 \times B^2(K^{*+} \to K^0\pi^+)$		$(1.2 \pm 0.5)\%$		273
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		$< 7.9 \times 10^{-3}$	CL=90%	678
$K^+K^-\pi^+\pi^+\pi^-$		—		600
$\phi\pi^+\pi^+\pi^- \times B(\phi \to K^+K^-)$		$< 1 \times 10^{-3}$	CL=90%	565
$K^+K^-\pi^+\pi^+\pi^-$ nonresonant		$< 3\%$	CL=90%	600

Fractions of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\phi\pi^+$		$(6.1 \pm 0.6) \times 10^{-3}$		647
$\phi\pi^+\pi^0$		$(2.3 \pm 1.0)\%$		619
$\phi\rho^+$		$< 1.4\%$	CL=90%	268
$\phi\pi^+\pi^+\pi^-$		$< 2 \times 10^{-3}$	CL=90%	565
$K^+\overline{K}^*(892)^0$		$(4.2 \pm 0.5) \times 10^{-3}$		610
$K^*(892)^+\overline{K}^0$		$(3.2 \pm 1.5)\%$		611
$K^*(892)^+\overline{K}^*(892)^0$		$(2.6 \pm 1.1)\%$		273

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) or Lepton number (*L*) violating modes

$K^+\pi^+\pi^-$	*DC*		$(6.8 \pm 1.5) \times 10^{-4}$		845
$K^+\rho^0$	*DC*		$(2.5 \pm 1.2) \times 10^{-4}$		681
$K^*(892)^0\pi^+$	*DC*		$(3.6 \pm 1.6) \times 10^{-4}$		712
$K^+\pi^+\pi^-$ nonresonant	*DC*		$(2.4 \pm 1.2) \times 10^{-4}$		845
$K^+K^+K^-$	*DC*		$< 1.4 \times 10^{-4}$	CL=90%	550
ϕK^+	*DC*		$< 1.3 \times 10^{-4}$	CL=90%	527
$\pi^+e^+e^-$	*C1*		$< 6.6 \times 10^{-5}$	CL=90%	929
$\pi^+\mu^+\mu^-$	*C1*		$< 1.8 \times 10^{-5}$	CL=90%	917
$\rho^+\mu^+\mu^-$	*C1*		$< 5.6 \times 10^{-4}$	CL=90%	759
$K^+e^+e^-$		[ss]	$< 2.0 \times 10^{-4}$	CL=90%	869
$K^+\mu^+\mu^-$		[ss]	$< 9.7 \times 10^{-5}$	CL=90%	856
$\pi^+e^+\mu^-$	*LF*		$< 1.1 \times 10^{-4}$	CL=90%	926
$\pi^+e^-\mu^+$	*LF*		$< 1.3 \times 10^{-4}$	CL=90%	926
$K^+e^+\mu^-$	*LF*		$< 1.3 \times 10^{-4}$	CL=90%	866

$K^+ e^- \mu^+$	LF	$< 1.2 \times 10^{-4}$	CL=90%	866
$\pi^- e^+ e^+$	L	$< 1.1 \times 10^{-4}$	CL=90%	929
$\pi^- \mu^+ \mu^+$	L	$< 8.7 \times 10^{-5}$	CL=90%	917
$\pi^- e^+ \mu^+$	L	$< 1.1 \times 10^{-4}$	CL=90%	926
$\rho^- \mu^+ \mu^+$	L	$< 5.6 \times 10^{-4}$	CL=90%	759
$K^- e^+ e^+$	L	$< 1.2 \times 10^{-4}$	CL=90%	869
$K^- \mu^+ \mu^+$	L	$< 1.2 \times 10^{-4}$	CL=90%	856
$K^- e^+ \mu^+$	L	$< 1.3 \times 10^{-4}$	CL=90%	866
$K^*(892)^- \mu^+ \mu^+$	L	$< 8.5 \times 10^{-4}$	CL=90%	703

D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.6 \pm 0.5$ MeV (S = 1.1)
$m_{D^\pm} - m_{D^0} = 4.76 \pm 0.10$ MeV (S = 1.1)
Mean life $\tau = (0.415 \pm 0.004) \times 10^{-12}$ s
$c\tau = 124.4\ \mu$m
$\left|m_{D_1^0} - m_{D_2^0}\right| < 24 \times 10^{10}\ \hbar\ s^{-1}$, CL = 90% [tt]
$\left|\Gamma_{D_1^0} - \Gamma_{D_2^0}\right|/\Gamma_{D^0} < 0.20$, CL = 90% [tt]
$\Gamma(K^+ \ell^- \overline{\nu}_\ell$ (via $\overline{D}^0$))/$\Gamma(K^- \ell^+ \nu_\ell) < 0.005$, CL = 90%
$\frac{\Gamma(K^+\pi^- \text{ or } K^+\pi^-\pi^+\pi^- (\text{via } \overline{D}^0))}{\Gamma(K^-\pi^+ \text{ or } K^-\pi^+\pi^+\pi^-)} < 0.0085$ (or < 0.0037), CL = 90% [uu]

CP-violation decay-rate asymmetries

$A_{CP}(K^+ K^-) = 0.026 \pm 0.035$
$A_{CP}(\pi^+ \pi^-) = -0.05 \pm 0.08$
$A_{CP}(K_S^0 \phi) = -0.03 \pm 0.09$
$A_{CP}(K_S^0 \pi^0) = -0.018 \pm 0.030$

$\overline{D}^0$ modes are charge conjugates of the modes below.

D^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
		Inclusive modes		
e^+ anything		(6.75 ± 0.29) %		–
μ^+ anything		(6.6 ± 0.8) %		–
K^- anything		(53 ± 4) %	S=1.3	–
$\overline{K}^0$ anything + K^0 anything		(42 ± 5) %		–
K^+ anything		$(3.4 {}^{+0.6}_{-0.4})$ %		–
η anything	[nn]	< 13 %	CL=90%	–
		Semileptonic modes		
$K^- \ell^+ \nu_\ell$	[oo]	(3.50 ± 0.17) %	S=1.3	867
$K^- e^+ \nu_e$		(3.66 ± 0.18) %		867
$K^- \mu^+ \nu_\mu$		(3.23 ± 0.17) %		863
$K^- \pi^0 e^+ \nu_e$		$(1.6 {}^{+1.3}_{-0.5})$ %		861
$\overline{K}^0 \pi^- e^+ \nu_e$		$(2.8 {}^{+1.7}_{-0.9})$ %		860
$\overline{K}^*(892)^- e^+ \nu_e$ × B($K^{*-} \to \overline{K}^0 \pi^-$)		(1.35 ± 0.22) %		719
$K^*(892)^- \ell^+ \nu_\ell$		—		–
$\overline{K}^*(892)^0 \pi^- e^+ \nu_e$		—		708
$K^- \pi^+ \pi^- \mu^+ \nu_\mu$		$< 1.2 \times 10^{-3}$	CL=90%	821
$(\overline{K}^*(892)\pi)^- \mu^+ \nu_\mu$		$< 1.4 \times 10^{-3}$	CL=90%	693
$\pi^- e^+ \nu_e$		$(3.7 \pm 0.6) \times 10^{-3}$		927

A fraction of the following resonance mode has already appeared above as a submode of a charged-particle mode.

$K^*(892)^- e^+ \nu_e$		(2.02 ± 0.33) %		719
		Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$		
$K^- \pi^+$		(3.85 ± 0.09) %		861
$\overline{K}^0 \pi^0$		(2.12 ± 0.21) %	S=1.1	860
$\overline{K}^0 \pi^+ \pi^-$	[qq]	(5.4 ± 0.4) %	S=1.2	842
$\overline{K}^0 \rho^0$		(1.21 ± 0.17) %		676
$\overline{K}^0 f_0(980)$ × B($f_0 \to \pi^+ \pi^-$)		$(3.0 \pm 0.8) \times 10^{-3}$		549
$\overline{K}^0 f_2(1270)$ × B($f_2 \to \pi^+ \pi^-$)		$(2.4 \pm 0.9) \times 10^{-3}$		263
$\overline{K}^0 f_0(1370)$ × B($f_0 \to \pi^+ \pi^-$)		$(4.3 \pm 1.3) \times 10^{-3}$		–
$K^*(892)^- \pi^+$ × B($K^{*-} \to \overline{K}^0 \pi^-$)		(3.4 ± 0.3) %		711
$K_0^*(1430)^- \pi^+$ × B($K_0^*(1430)^- \to \overline{K}^0 \pi^-$)		$(6.4 \pm 1.6) \times 10^{-3}$		364
$\overline{K}^0 \pi^+ \pi^-$ nonresonant		(1.47 ± 0.24) %		842
$K^- \pi^+ \pi^0$	[qq]	(13.9 ± 0.9) %	S=1.3	844
$K^- \rho^+$		(10.8 ± 1.0) %		678
$K^*(892)^- \pi^+$ × B($K^{*-} \to K^- \pi^0$)		(1.7 ± 0.2) %		711
$\overline{K}^*(892)^0 \pi^0$ × B($\overline{K}^{*0} \to K^- \pi^+$)		(2.1 ± 0.3) %		709
$K^- \pi^+ \pi^0$ nonresonant		$(6.9 \pm 2.5) \times 10^{-3}$		844
$\overline{K}^0 \pi^0 \pi^0$		—		843
$\overline{K}^*(892)^0 \pi^0$ × B($\overline{K}^{*0} \to \overline{K}^0 \pi^0$)		(1.1 ± 0.2) %		709
$\overline{K}^0 \pi^0 \pi^0$ nonresonant		$(7.9 \pm 2.1) \times 10^{-3}$		843
$K^- \pi^+ \pi^+ \pi^-$	[qq]	(7.6 ± 0.4) %	S=1.1	812
$K^- \pi^+ \rho^0$ total		(6.3 ± 0.4) %		612
$K^- \pi^+ \rho^0$ 3-body		$(4.8 \pm 2.1) \times 10^{-3}$		612
$\overline{K}^*(892)^0 \rho^0$ × B($\overline{K}^{*0} \to K^- \pi^+$)		$(9.8 \pm 2.2) \times 10^{-3}$		418
$K^- a_1(1260)^+$ × B($a_1(1260)^+ \to \pi^+ \pi^+ \pi^-$)		(3.6 ± 0.6) %		327
$\overline{K}^*(892)^0 \pi^+ \pi^-$ total × B($\overline{K}^{*0} \to K^- \pi^+$)		(1.5 ± 0.4) %		683
$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body × B($\overline{K}^{*0} \to K^- \pi^+$)		$(9.5 \pm 2.1) \times 10^{-3}$		683
$K_1(1270)^- \pi^+$ × B($K_1(1270)^- \to K^- \pi^+ \pi^-$)	[rr]	$(3.6 \pm 1.0) \times 10^{-3}$		483
$K^- \pi^+ \pi^+ \pi^-$ nonresonant		(1.76 ± 0.25) %		812
$\overline{K}^0 \pi^+ \pi^- \pi^0$	[qq]	(10.0 ± 1.2) %		812
$\overline{K}^0 \eta$ × B($\eta \to \pi^+ \pi^- \pi^0$)		$(1.6 \pm 0.3) \times 10^{-3}$		772
$\overline{K}^0 \omega$ × B($\omega \to \pi^+ \pi^- \pi^0$)		(1.9 ± 0.4) %		670
$K^*(892)^- \rho^+$ × B($K^{*-} \to \overline{K}^0 \pi^-$)		(4.1 ± 1.6) %		422
$\overline{K}^*(892)^0 \rho^0$ × B($\overline{K}^{*0} \to \overline{K}^0 \pi^0$)		$(4.9 \pm 1.1) \times 10^{-3}$		418
$K_1(1270)^- \pi^+$ × B($K_1(1270)^- \to \overline{K}^0 \pi^- \pi^0$)	[rr]	$(5.1 \pm 1.4) \times 10^{-3}$		483
$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body × B($\overline{K}^{*0} \to \overline{K}^0 \pi^0$)		$(4.8 \pm 1.1) \times 10^{-3}$		683
$\overline{K}^0 \pi^+ \pi^- \pi^0$ nonresonant		(2.1 ± 2.1) %		812
$K^- \pi^+ \pi^0 \pi^0$		(15 ± 5) %		815
$K^- \pi^+ \pi^+ \pi^- \pi^0$		(4.1 ± 0.4) %		771
$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$ × B($\overline{K}^{*0} \to K^- \pi^+$)		(1.2 ± 0.6) %		641
$\overline{K}^*(892)^0 \eta$ × B($\overline{K}^{*0} \to K^- \pi^+$) × B($\eta \to \pi^+ \pi^- \pi^0$)		$(2.9 \pm 0.8) \times 10^{-3}$		580
$K^- \pi^+ \omega$ × B($\omega \to \pi^+ \pi^- \pi^0$)		(2.7 ± 0.5) %		605
$\overline{K}^*(892)^0 \omega$ × B($\overline{K}^{*0} \to K^- \pi^+$) × B($\omega \to \pi^+ \pi^- \pi^0$)		$(7 \pm 3) \times 10^{-3}$		406
$\overline{K}^0 \pi^+ \pi^+ \pi^- \pi^-$		$(5.8 \pm 1.6) \times 10^{-3}$		768
$\overline{K}^0 \pi^+ \pi^- \pi^0 \pi^0 (\pi^0)$		$(10.6 {}^{+7.3}_{-3.0})$ %		771
$\overline{K}^0 K^+ K^-$		$(9.4 \pm 1.0) \times 10^{-3}$		544
$\overline{K}^0 \phi$ × B($\phi \to K^+ K^-$)		$(4.3 \pm 0.5) \times 10^{-3}$		520
$\overline{K}^0 K^+ K^-$ non-ϕ		$(5.1 \pm 0.8) \times 10^{-3}$		544
$K_S^0 K_S^0 K_S^0$		$(8.4 \pm 1.5) \times 10^{-4}$		538
$K^+ K^- K^- \pi^+$		$(2.1 \pm 0.5) \times 10^{-4}$		434
$K^+ K^- \overline{K}^0 \pi^0$		$(7.2 {}^{+4.8}_{-3.5}) \times 10^{-3}$		435

Fractions of many of the following modes with resonances have already appeared above as submodes of particular charged-particle modes. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)

$\overline{K}^0 \eta$		$(7.1 \pm 1.0) \times 10^{-3}$		772
$\overline{K}^0 \rho^0$		(1.21 ± 0.17) %		676
$K^- \rho^+$		(10.8 ± 1.0) %	S=1.2	678
$\overline{K}^0 \omega$		(2.1 ± 0.4) %		670
$\overline{K}^0 \eta'(958)$		(1.72 ± 0.26) %		565
$\overline{K}^0 f_0(980)$		$(5.7 \pm 1.6) \times 10^{-3}$		549
$\overline{K}^0 \phi$		$(8.6 \pm 1.0) \times 10^{-3}$		520
$K^- a_1(1260)^+$		(7.3 ± 1.1) %		327
$\overline{K}^0 a_1(1260)^0$		< 1.9 %	CL=90%	322
$\overline{K}^0 f_2(1270)$		$(4.2 \pm 1.5) \times 10^{-3}$		263
$K^- a_2(1320)^+$		$< 2 \times 10^{-3}$	CL=90%	197
$\overline{K}^0 f_0(1370)$		$(7.0 \pm 2.1) \times 10^{-3}$		–
$K^*(892)^- \pi^+$		(5.1 ± 0.4) %	S=1.2	711
$\overline{K}^*(892)^0 \pi^0$		(3.2 ± 0.4) %		709
$\overline{K}^*(892)^0 \pi^+ \pi^-$ total		(2.3 ± 0.5) %		683
$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body		(1.43 ± 0.32) %		683

$K^- \pi^+ \rho^0$ total			(6.3 ± 0.4) %		612
$K^- \pi^+ \rho^0$ 3-body			$(4.8 \pm 2.1) \times 10^{-3}$		612
$\overline{K}^*(892)^0 \rho^0$			(1.47 ± 0.33) %		418
$\overline{K}^*(892)^0 \rho^0$ transverse			(1.5 ± 0.5) %		418
$\overline{K}^*(892)^0 \rho^0$ *S*-wave			(2.8 ± 0.6) %		418
$\overline{K}^*(892)^0 \rho^0$ *S*-wave long.			$< 3 \times 10^{-3}$	CL=90%	418
$\overline{K}^*(892)^0 \rho^0$ *P*-wave			$< 3 \times 10^{-3}$	CL=90%	418
$\overline{K}^*(892)^0 \rho^0$ *D*-wave			(1.9 ± 0.6) %		418
$K^*(892)^- \rho^+$			(6.1 ± 2.4) %		422
$K^*(892)^- \rho^+$ longitudinal			(2.9 ± 1.2) %		422
$K^*(892)^- \rho^+$ transverse			(3.2 ± 1.8) %		422
$K^*(892)^- \rho^+$ *P*-wave			< 1.5 %	CL=90%	422
$K^- \pi^+ f_0(980)$			< 1.1 %	CL=90%	459
$\overline{K}^*(892)^0 f_0(980)$			$< 7 \times 10^{-3}$	CL=90%	–
$K_1(1270)^- \pi^+$		[rr]	(1.06 ± 0.29) %		483
$K_1(1400)^- \pi^+$			< 1.2 %	CL=90%	386
$\overline{K}_1(1400)^0 \pi^0$			< 3.7 %	CL=90%	387
$K^*(1410)^- \pi^+$			< 1.2 %	CL=90%	378
$K_0^*(1430)^- \pi^+$			(1.04 ± 0.26) %		364
$K_2^*(1430)^- \pi^+$			$< 8 \times 10^{-3}$	CL=90%	367
$\overline{K}_2^*(1430)^0 \pi^0$			$< 4 \times 10^{-3}$	CL=90%	363
$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$			(1.8 ± 0.9) %		641
$\overline{K}^*(892)^0 \eta$			(1.9 ± 0.5) %		580
$K^- \pi^+ \omega$			(3.0 ± 0.6) %		605
$\overline{K}^*(892)^0 \omega$			(1.1 ± 0.5) %		406
$K^- \pi^+ \eta'(958)$			$(7.0 \pm 1.8) \times 10^{-3}$		479
$\overline{K}^*(892)^0 \eta'(958)$			$< 1.1 \times 10^{-3}$	CL=90%	99

Pionic modes

$\pi^+ \pi^-$			$(1.53 \pm 0.09) \times 10^{-3}$		922
$\pi^0 \pi^0$			$(8.5 \pm 2.2) \times 10^{-4}$		922
$\pi^+ \pi^- \pi^0$			(1.6 ± 1.1) %	S=2.7	907
$\pi^+ \pi^+ \pi^- \pi^-$			$(7.4 \pm 0.6) \times 10^{-3}$		879
$\pi^+ \pi^+ \pi^- \pi^- \pi^0$			(1.9 ± 0.4) %		844
$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$			$(4.0 \pm 3.0) \times 10^{-4}$		795

Hadronic modes with a $K\overline{K}$ pair

$K^+ K^-$			$(4.27 \pm 0.16) \times 10^{-3}$		791
$K^0 \overline{K}^0$			$(6.5 \pm 1.8) \times 10^{-4}$	S=1.2	788
$K^0 K^- \pi^+$			$(6.4 \pm 1.0) \times 10^{-3}$	S=1.1	739
$\overline{K}^*(892)^0 K^0$ $\times\ B(\overline{K}^{*0} \to K^- \pi^+)$			$< 1.1 \times 10^{-3}$	CL=90%	605
$K^*(892)^+ K^-$ $\times\ B(K^{*+} \to K^0 \pi^+)$			$(2.3 \pm 0.5) \times 10^{-3}$		610
$K^0 K^- \pi^+$ nonresonant			$(2.3 \pm 2.3) \times 10^{-3}$		739
$\overline{K}^0 K^+ \pi^-$			$(5.0 \pm 1.0) \times 10^{-3}$		739
$K^*(892)^0 \overline{K}^0$ $\times\ B(K^{*0} \to K^+ \pi^-)$			$< 5 \times 10^{-4}$	CL=90%	605
$K^*(892)^- K^+$ $\times\ B(K^{*-} \to \overline{K}^0 \pi^-)$			$(1.2 \pm 0.7) \times 10^{-3}$		610
$\overline{K}^0 K^+ \pi^-$ nonresonant			$(3.9\ {}^{+2.3}_{-1.9}) \times 10^{-3}$		739
$K^+ K^- \pi^0$			$(1.3 \pm 0.4) \times 10^{-3}$		742
$K_S^0 K_S^0 \pi^0$			$< 5.9 \times 10^{-4}$		739
$K^+ K^- \pi^+ \pi^-$		[vv]	$(2.52 \pm 0.24) \times 10^{-3}$		676
$\phi \pi^+ \pi^- \times B(\phi \to K^+ K^-)$			$(5.3 \pm 1.4) \times 10^{-4}$		614
$\phi \rho^0 \times B(\phi \to K^+ K^-)$			$(3.0 \pm 1.6) \times 10^{-4}$		260
$K^+ K^- \rho^0$ 3-body			$(9.1 \pm 2.3) \times 10^{-4}$		309
$K^*(892)^0 K^- \pi^+$ +c.c. $\times\ B(K^{*0} \to K^+ \pi^-)$		[ww]	$< 5 \times 10^{-4}$		528
$K^*(892)^0 \overline{K}^*(892)^0$ $\times\ B^2(K^{*0} \to K^+ \pi^-)$			$(6 \pm 2) \times 10^{-4}$		257
$K^+ K^- \pi^+ \pi^-$ non-ϕ			—		676
$K^+ K^- \pi^+ \pi^-$ nonresonant			$< 8 \times 10^{-4}$	CL=90%	676
$K^0 \overline{K}^0 \pi^+ \pi^-$			$(6.9 \pm 2.7) \times 10^{-3}$		673
$K^+ K^- \pi^+ \pi^- \pi^0$			$(3.1 \pm 2.0) \times 10^{-3}$		600

Fractions of most of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\overline{K}^*(892)^0 K^0$			$< 1.6 \times 10^{-3}$	CL=90%	605
$K^*(892)^+ K^-$			$(3.5 \pm 0.8) \times 10^{-3}$		610
$K^*(892)^0 \overline{K}^0$			$< 8 \times 10^{-4}$	CL=90%	605
$K^*(892)^- K^+$			$(1.8 \pm 1.0) \times 10^{-3}$		610
$\phi \pi^0$			$< 1.4 \times 10^{-3}$	CL=90%	644
$\phi \eta$			$< 2.8 \times 10^{-3}$	CL=90%	489
$\phi \omega$			$< 2.1 \times 10^{-3}$	CL=90%	239
$\phi \pi^+ \pi^-$			$(1.08 \pm 0.29) \times 10^{-3}$		614
$\phi \rho^0$			$(6 \pm 3) \times 10^{-4}$		260
$\phi \pi^+ \pi^-$ 3-body			$(7 \pm 5) \times 10^{-4}$		614
$K^*(892)^0 K^- \pi^+$ + c.c.		[ww]	$< 8 \times 10^{-4}$	CL=90%	–
$K^*(892)^0 \overline{K}^*(892)^0$			$(1.4 \pm 0.5) \times 10^{-3}$		257

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 2$ forbidden via mixing (*C2M*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) violating modes

$K^+ \ell^- \overline{\nu}_\ell$ (via $\overline{D}^0$)	*C2M*		$< 1.7 \times 10^{-4}$	CL=90%	–
$K^+ \pi^-$ or $K^+ \pi^- \pi^+ \pi^-$ (via $\overline{D}^0$)	*C2M*		$< 1.0 \times 10^{-3}$	CL=90%	–
$K^+ \pi^-$	*DC*		$(2.8 \pm 0.9) \times 10^{-4}$		861
$K^+ \pi^-$ (via $\overline{D}^0$)			$< 1.9 \times 10^{-4}$	CL=90%	861
$K^+ \pi^- \pi^+ \pi^-$	*DC*		$(1.9 \pm 2.7) \times 10^{-4}$		812
$K^+ \pi^- \pi^+ \pi^-$ (via $\overline{D}^0$)			$< 4 \times 10^{-4}$	CL=90%	812
μ^- anything (via $\overline{D}^0$)			$< 4 \times 10^{-4}$	CL=90%	–
$e^+ e^-$	*C1*		$< 1.3 \times 10^{-5}$	CL=90%	932
$\mu^+ \mu^-$	*C1*		$< 4.1 \times 10^{-6}$	CL=90%	926
$\pi^0 e^+ e^-$	*C1*		$< 4.5 \times 10^{-5}$	CL=90%	927
$\pi^0 \mu^+ \mu^-$	*C1*		$< 1.8 \times 10^{-4}$	CL=90%	915
$\eta e^+ e^-$	*C1*		$< 1.1 \times 10^{-4}$	CL=90%	852
$\eta \mu^+ \mu^-$	*C1*		$< 5.3 \times 10^{-4}$	CL=90%	838
$\rho^0 e^+ e^-$	*C1*		$< 1.0 \times 10^{-4}$	CL=90%	773
$\rho^0 \mu^+ \mu^-$	*C1*		$< 2.3 \times 10^{-4}$	CL=90%	756
$\omega e^+ e^-$	*C1*		$< 1.8 \times 10^{-4}$	CL=90%	768
$\omega \mu^+ \mu^-$	*C1*		$< 8.3 \times 10^{-4}$	CL=90%	751
$\phi e^+ e^-$	*C1*		$< 5.2 \times 10^{-5}$	CL=90%	654
$\phi \mu^+ \mu^-$	*C1*		$< 4.1 \times 10^{-4}$	CL=90%	631
$\overline{K}^0 e^+ e^-$		[ss]	$< 1.1 \times 10^{-4}$	CL=90%	866
$\overline{K}^0 \mu^+ \mu^-$		[ss]	$< 2.6 \times 10^{-4}$	CL=90%	852
$\overline{K}^*(892)^0 e^+ e^-$		[ss]	$< 1.4 \times 10^{-4}$	CL=90%	717
$\overline{K}^*(892)^0 \mu^+ \mu^-$		[ss]	$< 1.18 \times 10^{-3}$	CL=90%	698
$\pi^+ \pi^- \pi^0 \mu^+ \mu^-$	*C1*		$< 8.1 \times 10^{-4}$	CL=90%	863
$\mu^\pm e^\mp$	*LF*	[gg]	$< 1.9 \times 10^{-5}$	CL=90%	929
$\pi^0 e^\pm \mu^\mp$	*LF*	[gg]	$< 8.6 \times 10^{-5}$	CL=90%	924
$\eta e^\pm \mu^\mp$	*LF*	[gg]	$< 1.0 \times 10^{-4}$	CL=90%	848
$\rho^0 e^\pm \mu^\mp$	*LF*	[gg]	$< 4.9 \times 10^{-5}$	CL=90%	769
$\omega e^\pm \mu^\mp$	*LF*	[gg]	$< 1.2 \times 10^{-4}$	CL=90%	764
$\phi e^\pm \mu^\mp$	*LF*	[gg]	$< 3.4 \times 10^{-5}$	CL=90%	648
$\overline{K}^0 e^\pm \mu^\mp$	*LF*	[gg]	$< 1.0 \times 10^{-4}$	CL=90%	862
$\overline{K}^*(892)^0 e^\pm \mu^\mp$	*LF*	[gg]	$< 1.0 \times 10^{-4}$	CL=90%	712

$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, *J*, *P* need confirmation.

Mass $m = 2006.7 \pm 0.5$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07$ MeV
Full width $\Gamma < 2.1$ MeV, CL = 90%

$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	*p* (MeV/*c*)
$D^0 \pi^0$	(61.9 ± 2.9) %	43
$D^0 \gamma$	(38.1 ± 2.9) %	137

$D^*(2010)^\pm$

$I(J^P) = \frac{1}{2}(1^-)$
I, *J*, *P* need confirmation.

Mass $m = 2010.0 \pm 0.5$ MeV (S = 1.1)
$m_{D^*(2010)^+} - m_{D^+} = 140.64 \pm 0.10$ MeV (S = 1.1)
$m_{D^*(2010)^+} - m_{D^0} = 145.397 \pm 0.030$ MeV
Full width $\Gamma < 0.131$ MeV, CL = 90%

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)	*p* (MeV/*c*)
$D^0 \pi^+$	(68.3 ± 1.4) %	39
$D^+ \pi^0$	(30.6 ± 2.5) %	38
$D^+ \gamma$	$(1.1^{+2.1}_{-0.7})$ %	136

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Mass $m = 2422.2 \pm 1.8$ MeV (S = 1.2)
Full width $\Gamma = 18.9^{+4.6}_{-3.5}$ MeV

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

$D_1(2420)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+\pi^-$	seen	355
$D^+\pi^-$	not seen	474

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

Mass $m = 2458.9 \pm 2.0$ MeV (S = 1.2)
Full width $\Gamma = 23 \pm 5$ MeV

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

$D_2^*(2460)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^+\pi^-$	seen	503
$D^*(2010)^+\pi^-$	seen	387

$D_2^*(2460)^\pm$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

Mass $m = 2459 \pm 4$ MeV (S = 1.7)
$m_{D_2^*(2460)^\pm} - m_{D_2^*(2460)^0} = 0.9 \pm 3.3$ MeV (S = 1.1)
Full width $\Gamma = 25^{+8}_{-7}$ MeV

$D_2^*(2460)^-$ modes are charge conjugates of modes below.

$D_2^*(2460)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	seen	508
$D^{*0}\pi^+$	seen	390

CHARMED, STRANGE MESONS ($C = S = \pm 1$)

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}s$, similarly for D_s^*'s

$D_s^\pm$ was $F^\pm$

$I(J^P) = 0(0^-)$

Mass $m = 1968.5 \pm 0.6$ MeV (S = 1.1)
$m_{D_s^\pm} - m_{D^\pm} = 99.2 \pm 0.5$ MeV (S = 1.1)
Mean life $\tau = (0.467 \pm 0.017) \times 10^{-12}$ s
$c\tau = 140$ μm

D_s^+ form factors

$r_2 = 1.6 \pm 0.4$
$r_v = 1.5 \pm 0.5$
$\Gamma_L/\Gamma_T = 0.72 \pm 0.18$

Branching fractions for modes with a resonance in the final state include all the decay modes of the resonance. D_s^- modes are charge conjugates of the modes below.

D_s^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes				
K^- anything		$(13\ ^{+14}_{-12})$ %		–
$\overline{K}^0$ anything + K^0 anything		(39 ± 28) %		–
K^+ anything		$(20\ ^{+18}_{-14})$ %		–
non-$K\overline{K}$ anything		(64 ± 17) %		–
e^+ anything		$(8\ ^{+6}_{-5})$ %		–
ϕ anything		$(18\ ^{+15}_{-10})$ %		–
Leptonic and semileptonic modes				
$\mu^+\nu_\mu$		$(4.0\ ^{+2.2}_{-2.0}) \times 10^{-3}$	S=1.4	981
$\tau^+\nu_\tau$		(7 ± 4) %		182
$\phi\ell^+\nu_\ell$	[xx]	(2.0 ± 0.5) %		–
$\eta\ell^+\nu_\ell$ + $\eta'(958)\ell^+\nu_\ell$	[xx]	(3.4 ± 1.0) %		–
$\eta\ell^+\nu_\ell$		(2.5 ± 0.7) %		–
$\eta'(958)\ell^+\nu_\ell$		$(8.8 \pm 3.4) \times 10^{-3}$		–
Hadronic modes with a $K\overline{K}$ pair (including from a ϕ)				
$K^+\overline{K}^0$		(3.6 ± 1.1) %		850
$K^+K^-\pi^+$	[qq]	(4.4 ± 1.2) %	S=1.1	805
$\phi\pi^+$	[yy]	(3.6 ± 0.9) %		712
$K^+\overline{K}^*(892)^0$	[yy]	(3.3 ± 0.9) %		682
$f_0(980)\pi^+$	[yy]	(1.8 ± 0.8) %	S=1.3	732
$K^+\overline{K}_0^*(1430)^0$	[yy]	$(7 \pm 4) \times 10^{-3}$		186
$f_J(1710)\pi^+ \to K^+K^-\pi^+$	[zz]	$(1.5 \pm 1.9) \times 10^{-3}$		204
$K^+K^-\pi^+$ nonresonant		$(9 \pm 4) \times 10^{-3}$		805
$K^0\overline{K}^0\pi^+$		—		802
$K^*(892)^+\overline{K}^0$	[yy]	(4.3 ± 1.4) %		683
$K^+K^-\pi^+\pi^0$		—		748
$\phi\pi^+\pi^0$	[yy]	(9 ± 5) %		687
$\phi\rho^+$	[yy]	(6.7 ± 2.3) %		407
$\phi\pi^+\pi^0$ 3-body	[yy]	< 2.6 %	CL=90%	687
$K^+K^-\pi^+\pi^0$ non-ϕ		< 9 %	CL=90%	748
$K^+\overline{K}^0\pi^+\pi^-$		< 2.8 %	CL=90%	744
$K^0K^-\pi^+\pi^+$		(4.3 ± 1.5) %		744
$K^*(892)^+\overline{K}^*(892)^0$	[yy]	(5.8 ± 2.5) %		412
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 2.9 %	CL=90%	744
$K^+K^-\pi^+\pi^+\pi^-$		$(8.3 \pm 3.3) \times 10^{-3}$		673
$\phi\pi^+\pi^+\pi^-$	[yy]	(1.18 ± 0.35) %		640
$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ		$(3.0\ ^{+3.0}_{-2.0}) \times 10^{-3}$		673
Hadronic modes without K's				
$\pi^+\pi^+\pi^-$		(1.0 ± 0.4) %	S=1.2	959
$\rho^0\pi^+$		$< 8 \times 10^{-4}$	CL=90%	827
$f_0(980)\pi^+$	[yy]	(1.8 ± 0.8) %	S=1.7	732
$f_2(1270)\pi^+$	[yy]	$(2.3 \pm 1.3) \times 10^{-3}$		559
$f_0(1500)\pi^+ \to \pi^+\pi^-\pi^+$	[aaa]	$(2.8 \pm 1.6) \times 10^{-3}$		391
$\pi^+\pi^+\pi^-$ nonresonant		$< 2.8 \times 10^{-3}$	CL=90%	959
$\pi^+\pi^+\pi^-\pi^0$		< 12 %	CL=90%	935
$\eta\pi^+$	[yy]	(2.0 ± 0.6) %		902

$\omega\pi^+$		[yy] $(3.1 \pm 1.4) \times 10^{-3}$		822
$\pi^+\pi^+\pi^+\pi^-\pi^-$		$(6.9 \pm 3.0) \times 10^{-3}$		899
$\pi^+\pi^+\pi^-\pi^0\pi^0$		—		902
$\eta\rho^+$		[yy] (10.3 ± 3.2) %		727
$\eta\pi^+\pi^0$ 3-body		[yy] < 3.0 %	CL=90%	886
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		(4.9 ± 3.2) %		856
$\eta'(958)\pi^+$		[yy] (4.9 ± 1.8) %		743
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$		—		803
$\eta'(958)\rho^+$		[yy] (12 ± 4) %		470
$\eta'(958)\pi^+\pi^0$ 3-body		[yy] < 3.1 %	CL=90%	720

Modes with one or three *K*'s

$K^0\pi^+$		$< 8 \times 10^{-3}$	CL=90%	916
$K^+\pi^+\pi^-$		(1.0 ± 0.4) %		900
$K^+\rho^0$		$< 2.9 \times 10^{-3}$	CL=90%	747
$K^*(892)^0\pi^+$		[yy] $(6.5 \pm 2.8) \times 10^{-3}$		773
$K^+K^+K^-$		$< 6 \times 10^{-4}$	CL=90%	628
ϕK^+		[yy] $< 5 \times 10^{-4}$	CL=90%	607

$\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton number (*L*) violating modes

$\pi^+\mu^+\mu^-$		[ss] $< 4.3 \times 10^{-4}$	CL=90%	968
$K^+\mu^+\mu^-$	*C1*	$< 5.9 \times 10^{-4}$	CL=90%	909
$K^*(892)^+\mu^+\mu^-$	*C1*	$< 1.4 \times 10^{-3}$	CL=90%	765
$\pi^-\mu^+\mu^+$	*L*	$< 4.3 \times 10^{-4}$	CL=90%	968
$K^-\mu^+\mu^+$	*L*	$< 5.9 \times 10^{-4}$	CL=90%	909
$K^*(892)^-\mu^+\mu^+$	*L*	$< 1.4 \times 10^{-3}$	CL=90%	765

$D_s^{*\pm}$

$I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-.

Mass $m = 2112.4 \pm 0.7$ MeV (S = 1.1)
$m_{D_s^{*\pm}} - m_{D_s^\pm} = 143.8 \pm 0.4$ MeV
Full width $\Gamma < 1.9$ MeV, CL = 90%

D_s^{*-} modes are charge conjugates of the modes below.

D_s^{*+} DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D_s^+\gamma$	(94.2 ± 2.5) %	139
$D_s^+\pi^0$	(5.8 ± 2.5) %	48

$D_{s1}(2536)^\pm$

$I(J^P) = 0(1^+)$
J, *P* need confirmation.

Mass $m = 2535.35 \pm 0.34 \pm 0.5$ MeV
Full width $\Gamma < 2.3$ MeV, CL = 90%

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

$D_{s1}(2536)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+K^0$	seen	150
$D^*(2007)^0K^+$	seen	169
D^+K^0	not seen	382
D^0K^+	not seen	392
$D_s^{*+}\gamma$	possibly seen	389

$D_{sJ}(2573)^\pm$

$I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 2^+.

Mass $m = 2573.5 \pm 1.7$ MeV
Full width $\Gamma = 15^{+5}_{-4}$ MeV

$D_{sJ}(2573)^-$ modes are charge conjugates of the modes below.

$D_{sJ}(2573)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
D^0K^+	seen	436
$D^*(2007)^0K^+$	not seen	245

BOTTOM MESONS
($B = \pm1$)

$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $\bar{B}^0 = \bar{d}b$, $B^- = \bar{u}b$, similarly for B^*'s

B-particle organization

Many measurements of B decays involve admixtures of B hadrons. Previously we arbitrarily included such admixtures in the $B^\pm$ section, but because of their importance we have created two new sections: "$B^\pm/B^0$ Admixture" for $\Upsilon(4S)$ results and "$B^\pm/B^0/B_s^0/b$-baryon Admixture" for results at higher energies. Most inclusive decay branching fractions are found in the Admixture sections. B^0-$\bar{B}^0$ mixing data are found in the B^0 section, while B_s^0-$\bar{B}_s^0$ mixing data and B-$\bar{B}$ mixing data for a B^0/B_s^0 admixture are found in the B_s^0 section. *CP*-violation data are found in the B^0 section. *b*-baryons are found near the end of the Baryon section.

The organization of the B sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

[Production and Decay of *b*-flavored Hadrons]
[Semileptonic Decays of *B* Mesons]
- $B^\pm$
  - mass, mean life
  - branching fractions
- B^0
  - mass, mean life
  - branching fractions
  - polarization in B^0 decay
  - B^0-$\bar{B}^0$ mixing
  - [B^0-$\bar{B}^0$ Mixing and *CP* Violation in *B* Decay]
  - *CP* violation
- $B^\pm$ B^0 Admixtures
  - branching fractions
- $B^\pm/B^0/B_s^0/b$-baryon Admixtures
  - mean life
  - production fractions
  - branching fractions
- B^*
  - mass
- B_s^0
  - mass, mean life
  - branching fractions
  - polarization in B_s^0 decay
  - B_s^0-$\bar{B}_s^0$ mixing
  - B-$\bar{B}$ mixing (admixture of B^0, B_s^0)

At end of Baryon Listings:
- Λ_b
  - mass, mean life
  - branching fractions
- *b*-baryon Admixture
  - mean life
  - branching fractions

$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^{\pm}} = 5278.9 \pm 1.8$ MeV
Mean life $\tau_{B^{\pm}} = (1.65 \pm 0.04) \times 10^{-12}$ s
$c\tau = 495\ \mu$m

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^{\pm}/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes			
$\ell^+\nu_\ell$ anything	[pp] (10.3 ± 0.9) %		–
$\overline{D}^0\ell^+\nu_\ell$	[pp] (1.86 ± 0.33) %		–
$\overline{D}^*(2007)^0\ell^+\nu_\ell$	[pp] (5.3 ± 0.8) %		–
$\pi^0 e^+\nu_e$	$< 2.2 \times 10^{-3}$	CL=90%	2638
$\omega\ell^+\nu_\ell$	[pp] $< 2.1 \times 10^{-4}$	CL=90%	–
$\rho^0\ell^+\nu_\ell$	[pp] $< 2.1 \times 10^{-4}$	CL=90%	–
$e^+\nu_e$	$< 1.5 \times 10^{-5}$	CL=90%	2639
$\mu^+\nu_\mu$	$< 2.1 \times 10^{-5}$	CL=90%	2638
$\tau^+\nu_\tau$	$< 5.7 \times 10^{-4}$	CL=90%	2340
$e^+\nu_e\gamma$	$< 2.0 \times 10^{-4}$	CL=90%	–
$\mu^+\nu_\mu\gamma$	$< 5.2 \times 10^{-5}$	CL=90%	–
***D*, *D**, or *D*ₛ modes**			
$\overline{D}^0\pi^+$	$(5.3 \pm 0.5) \times 10^{-3}$		2308
$\overline{D}^0\rho^+$	(1.34 ± 0.18) %		2238
$\overline{D}^0\pi^+\pi^+\pi^-$	(1.1 ± 0.4) %		2289
$\overline{D}^0\pi^+\pi^+\pi^-$ nonresonant	$(5 \pm 4) \times 10^{-3}$		2289
$\overline{D}^0\pi^+\rho^0$	$(4.2 \pm 3.0) \times 10^{-3}$		2209
$\overline{D}^0 a_1(1260)^+$	$(5 \pm 4) \times 10^{-3}$		2123
$D^*(2010)^-\pi^+\pi^+$	$(2.1 \pm 0.6) \times 10^{-3}$		2247
$D^-\pi^+\pi^+$	$< 1.4 \times 10^{-3}$	CL=90%	2299
$\overline{D}^*(2007)^0\pi^+$	$(4.6 \pm 0.4) \times 10^{-3}$		2256
$D^*(2010)^+\pi^0$	$< 1.7 \times 10^{-4}$	CL=90%	2254
$\overline{D}^*(2007)^0\rho^+$	(1.55 ± 0.31) %		2183
$\overline{D}^*(2007)^0\pi^+\pi^+\pi^-$	$(9.4 \pm 2.6) \times 10^{-3}$		2236
$\overline{D}^*(2007)^0 a_1(1260)^+$	(1.9 ± 0.5) %		2062
$D^*(2010)^-\pi^+\pi^+\pi^0$	(1.5 ± 0.7) %		2235
$D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$	< 1 %	CL=90%	2217
$\overline{D}_1^*(2420)^0\pi^+$	$(1.5 \pm 0.6) \times 10^{-3}$	S=1.3	2081
$\overline{D}_1^*(2420)^0\rho^+$	$< 1.4 \times 10^{-3}$	CL=90%	1997
$\overline{D}_2^*(2460)^0\pi^+$	$< 1.3 \times 10^{-3}$	CL=90%	2064
$\overline{D}_2^*(2460)^0\rho^+$	$< 4.7 \times 10^{-3}$	CL=90%	1979
$\overline{D}^0 D_s^+$	(1.3 ± 0.4) %		1815
$\overline{D}^0 D_s^{*+}$	$(9 \pm 4) \times 10^{-3}$		1734
$\overline{D}^*(2007)^0 D_s^+$	(1.2 ± 0.5) %		1737
$\overline{D}^*(2007)^0 D_s^{*+}$	(2.7 ± 1.0) %		1650
$D_s^+\pi^0$	$< 2.0 \times 10^{-4}$	CL=90%	2270
$D_s^{*+}\pi^0$	$< 3.3 \times 10^{-4}$	CL=90%	2214
$D_s^+\eta$	$< 5 \times 10^{-4}$	CL=90%	2235
$D_s^{*+}\eta$	$< 8 \times 10^{-4}$	CL=90%	2177
$D_s^+\rho^0$	$< 4 \times 10^{-4}$	CL=90%	2198
$D_s^{*+}\rho^0$	$< 5 \times 10^{-4}$	CL=90%	2139
$D_s^+\omega$	$< 5 \times 10^{-4}$	CL=90%	2195
$D_s^{*+}\omega$	$< 7 \times 10^{-4}$	CL=90%	2136
$D_s^+ a_1(1260)^0$	$< 2.2 \times 10^{-3}$	CL=90%	2079
$D_s^{*+} a_1(1260)^0$	$< 1.6 \times 10^{-3}$	CL=90%	2014
$D_s^+\phi$	$< 3.2 \times 10^{-4}$	CL=90%	2141
$D_s^{*+}\phi$	$< 4 \times 10^{-4}$	CL=90%	2079
$D_s^+\overline{K}^0$	$< 1.1 \times 10^{-3}$	CL=90%	2241
$D_s^{*+}\overline{K}^0$	$< 1.1 \times 10^{-3}$	CL=90%	2184
$D_s^+\overline{K}^*(892)^0$	$< 5 \times 10^{-4}$	CL=90%	2171
$D_s^{*+}\overline{K}^*(892)^0$	$< 4 \times 10^{-4}$	CL=90%	2110
$D_s^-\pi^+K^+$	$< 8 \times 10^{-4}$	CL=90%	2222
$D_s^{*-}\pi^+K^+$	$< 1.2 \times 10^{-3}$	CL=90%	2164
$D_s^-\pi^+K^*(892)^+$	$< 6 \times 10^{-3}$	CL=90%	2137
$D_s^{*-}\pi^+K^*(892)^+$	$< 8 \times 10^{-3}$	CL=90%	2075
Charmonium modes			
$J/\psi(1S)K^+$	$(9.9 \pm 1.0) \times 10^{-4}$		1683
$J/\psi(1S)K^+\pi^+\pi^-$	$(1.4 \pm 0.6) \times 10^{-3}$		1612
$J/\psi(1S)K^*(892)^+$	$(1.47 \pm 0.27) \times 10^{-3}$		1571
$J/\psi(1S)\pi^+$	$(5.0 \pm 1.5) \times 10^{-5}$		1727
$J/\psi(1S)\rho^+$	$< 7.7 \times 10^{-4}$	CL=90%	1613
$J/\psi(1S)a_1(1260)^+$	$< 1.2 \times 10^{-3}$	CL=90%	1414
$\psi(2S)K^+$	$(6.9 \pm 3.1) \times 10^{-4}$	S=1.3	1284
$\psi(2S)K^*(892)^+$	$< 3.0 \times 10^{-3}$	CL=90%	1115
$\psi(2S)K^+\pi^+\pi^-$	$(1.9 \pm 1.2) \times 10^{-3}$		909
$\chi_{c1}(1P)K^+$	$(1.0 \pm 0.4) \times 10^{-3}$		1411
$\chi_{c1}(1P)K^*(892)^+$	$< 2.1 \times 10^{-3}$	CL=90%	1265
***K* or *K** modes**			
$K^0\pi^+$	$(2.3 \pm 1.1) \times 10^{-5}$		2614
$K^+\pi^0$	$< 1.6 \times 10^{-5}$	CL=90%	2615
$\eta' K^+$	$(6.5 \pm 1.7) \times 10^{-5}$		2528
$\eta' K^*(892)^+$	$< 1.3 \times 10^{-4}$	CL=90%	2472
ηK^+	$< 1.4 \times 10^{-5}$	CL=90%	2587
$\eta K^*(892)^+$	$< 3.0 \times 10^{-5}$	CL=90%	2534
$K^*(892)^0\pi^+$	$< 4.1 \times 10^{-5}$	CL=90%	2561
$K^*(892)^+\pi^0$	$< 9.9 \times 10^{-5}$	CL=90%	2562
$K^+\pi^-\pi^+$ nonresonant	$< 2.8 \times 10^{-5}$	CL=90%	2609
$K^-\pi^+\pi^+$ nonresonant	$< 5.6 \times 10^{-5}$	CL=90%	–
$K_1(1400)^0\pi^+$	$< 2.6 \times 10^{-3}$	CL=90%	2451
$K_2^*(1430)^0\pi^+$	$< 6.8 \times 10^{-4}$	CL=90%	2443
$K^+\rho^0$	$< 1.9 \times 10^{-5}$	CL=90%	2559
$K^0\rho^+$	$< 4.8 \times 10^{-5}$	CL=90%	2559
$K^*(892)^+\pi^+\pi^-$	$< 1.1 \times 10^{-3}$	CL=90%	2556
$K^*(892)^+\rho^0$	$< 9.0 \times 10^{-4}$	CL=90%	2505
$K_1(1400)^+\rho^0$	$< 7.8 \times 10^{-4}$	CL=90%	2389
$K_2^*(1430)^+\rho^0$	$< 1.5 \times 10^{-3}$	CL=90%	2382
$K^+\overline{K}^0$	$< 2.1 \times 10^{-5}$	CL=90%	2592
$K^+K^-\pi^+$ nonresonant	$< 7.5 \times 10^{-5}$	CL=90%	–
$K^+K^-K^+$	$< 2.0 \times 10^{-4}$	CL=90%	2522
$K^+\phi$	$< 1.2 \times 10^{-5}$	CL=90%	2516
$K^+K^-K^+$ nonresonant	$< 3.8 \times 10^{-5}$	CL=90%	2516
$K^*(892)^+K^+K^-$	$< 1.6 \times 10^{-3}$	CL=90%	2466
$K^*(892)^+\phi$	$< 7.0 \times 10^{-5}$	CL=90%	2460
$K_1(1400)^+\phi$	$< 1.1 \times 10^{-3}$	CL=90%	2339
$K_2^*(1430)^+\phi$	$< 3.4 \times 10^{-3}$	CL=90%	2332
$K^+ f_0(980)$	$< 8 \times 10^{-5}$	CL=90%	2524
$K^*(892)^+\gamma$	$(5.7 \pm 3.3) \times 10^{-5}$		2564
$K_1(1270)^+\gamma$	$< 7.3 \times 10^{-3}$	CL=90%	2486
$K_1(1400)^+\gamma$	$< 2.2 \times 10^{-3}$	CL=90%	2453
$K_2^*(1430)^+\gamma$	$< 1.4 \times 10^{-3}$	CL=90%	2447
$K^*(1680)^+\gamma$	$< 1.9 \times 10^{-3}$	CL=90%	2361
$K_3^*(1780)^+\gamma$	$< 5.5 \times 10^{-3}$	CL=90%	2343
$K_4^*(2045)^+\gamma$	$< 9.9 \times 10^{-3}$	CL=90%	2243
Light unflavored meson modes			
$\pi^+\pi^0$	$< 2.0 \times 10^{-5}$	CL=90%	2636
$\pi^+\pi^+\pi^-$	$< 1.3 \times 10^{-4}$	CL=90%	2630
$\rho^0\pi^+$	$< 4.3 \times 10^{-5}$	CL=90%	2582
$\pi^+ f_0(980)$	$< 1.4 \times 10^{-4}$	CL=90%	2547
$\pi^+ f_2(1270)$	$< 2.4 \times 10^{-4}$	CL=90%	2483
$\pi^+\pi^-\pi^+$ nonresonant	$< 4.1 \times 10^{-5}$	CL=90%	–
$\pi^+\pi^0\pi^0$	$< 8.9 \times 10^{-4}$	CL=90%	2631
$\rho^+\pi^0$	$< 7.7 \times 10^{-5}$	CL=90%	2582
$\pi^+\pi^-\pi^+\pi^0$	$< 4.0 \times 10^{-3}$	CL=90%	2621
$\rho^+\rho^0$	$< 1.0 \times 10^{-3}$	CL=90%	2525
$a_1(1260)^+\pi^0$	$< 1.7 \times 10^{-3}$	CL=90%	2494
$a_1(1260)^0\pi^+$	$< 9.0 \times 10^{-4}$	CL=90%	2494
$\omega\pi^+$	$< 4.0 \times 10^{-4}$	CL=90%	2580

$\eta\pi^+$		$< 1.5 \times 10^{-5}$	CL=90%	2609
$\eta'\pi^+$		$< 3.1 \times 10^{-5}$	CL=90%	2550
$\eta'\rho^+$		$< 4.7 \times 10^{-5}$	CL=90%	2493
$\eta\rho^+$		$< 3.2 \times 10^{-5}$	CL=90%	2554
$\pi^+\pi^+\pi^+\pi^-\pi^-$		$< 8.6 \times 10^{-4}$	CL=90%	2608
$\quad\rho^0 a_1(1260)^+$		$< 6.2 \times 10^{-4}$	CL=90%	2434
$\quad\rho^0 a_2(1320)^+$		$< 7.2 \times 10^{-4}$	CL=90%	2411
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		$< 6.3 \times 10^{-3}$	CL=90%	2592
$\quad a_1(1260)^+ a_1(1260)^0$		< 1.3 %	CL=90%	2335

Baryon modes

$p\overline{p}\pi^+$		$< 1.6 \times 10^{-4}$	CL=90%	2439
$\quad p\overline{p}\pi^+$ nonresonant		$< 5.3 \times 10^{-5}$	CL=90%	–
$p\overline{p}\pi^+\pi^+\pi^-$		$< 5.2 \times 10^{-4}$	CL=90%	2369
$p\overline{p}K^+$ nonresonant		$< 8.9 \times 10^{-5}$	CL=90%	–
$p\overline{\Lambda}$		$< 6 \times 10^{-5}$	CL=90%	2430
$p\overline{\Lambda}\pi^+\pi^-$		$< 2.0 \times 10^{-4}$	CL=90%	2367
$\overline{\Delta}^0 p$		$< 3.8 \times 10^{-4}$	CL=90%	2402
$\Delta^{++}\overline{p}$		$< 1.5 \times 10^{-4}$	CL=90%	2402
$\Lambda_c^- p\pi^+$		$(6.2 \pm 2.7) \times 10^{-4}$		–
$\Lambda_c^- p\pi^+\pi^0$		$< 3.12 \times 10^{-3}$	CL=90%	–
$\Lambda_c^- p\pi^+\pi^+\pi^-$		$< 1.46 \times 10^{-3}$	CL=90%	–
$\Lambda_c^- p\pi^+\pi^+\pi^-\pi^0$		< 1.34 %	CL=90%	–

Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

$\pi^+e^+e^-$	*B1*	$< 3.9 \times 10^{-3}$	CL=90%	2638
$\pi^+\mu^+\mu^-$	*B1*	$< 9.1 \times 10^{-3}$	CL=90%	2633
$K^+e^+e^-$	*B1*	$< 6 \times 10^{-5}$	CL=90%	2616
$K^+\mu^+\mu^-$	*B1*	$< 1.0 \times 10^{-5}$	CL=90%	2612
$K^*(892)^+e^+e^-$	*B1*	$< 6.9 \times 10^{-4}$	CL=90%	2564
$K^*(892)^+\mu^+\mu^-$	*B1*	$< 1.2 \times 10^{-3}$	CL=90%	2560
$\pi^+e^+\mu^-$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+e^-\mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2637
$K^+e^+\mu^-$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2615
$K^+e^-\mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2615
$\pi^-e^+e^+$	*L*	$< 3.9 \times 10^{-3}$	CL=90%	2638
$\pi^-\mu^+\mu^+$	*L*	$< 9.1 \times 10^{-3}$	CL=90%	2633
$\pi^-e^+\mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2637
$K^-e^+e^+$	*L*	$< 3.9 \times 10^{-3}$	CL=90%	2616
$K^-\mu^+\mu^+$	*L*	$< 9.1 \times 10^{-3}$	CL=90%	2612
$K^-e^+\mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%	2615

B^0

$I(J^P) = \frac{1}{2}(0^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0} = 5279.2 \pm 1.8$ MeV
$m_{B^0} - m_{B^\pm} = 0.35 \pm 0.29$ MeV (S = 1.1)
Mean life $\tau_{B^0} = (1.56 \pm 0.04) \times 10^{-12}$ s
$c\tau = 468\ \mu$m
$\tau_{B^+}/\tau_{B^0} = 1.02 \pm 0.04$ (average of direct and inferred)
$\tau_{B^+}/\tau_{B^0} = 1.04 \pm 0.04$ (direct measurements)
$\tau_{B^+}/\tau_{B^0} = 0.95^{+0.15}_{-0.12}$ (inferred from branching fractions)

B^0-$\overline{B}^0$ mixing parameters

$\chi_d = 0.172 \pm 0.010$
$\Delta m_{B^0} = m_{B^0_H} - m_{B^0_L} = (0.464 \pm 0.018) \times 10^{12}\ \hbar\ \mathrm{s}^{-1}$
$x_d = \Delta m_{B^0}/\Gamma_{B^0} = 0.723 \pm 0.032$

***CP* violation parameters**

$|\mathrm{Re}(\epsilon_{B^0})| = 0.002 \pm 0.008$

$\overline{B}^0$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the *B* are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed *D*, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\ell^+\nu_\ell$ anything	[*pp*]	(10.5 ± 0.8) %		–
$\quad D^-\ell^+\nu_\ell$	[*pp*]	(2.00 ± 0.25) %		–
$\quad D^*(2010)^-\ell^+\nu_\ell$	[*pp*]	(4.60 ± 0.27) %		–
$\quad\rho^-\ell^+\nu_\ell$	[*pp*]	$(2.5 {}^{+0.8}_{-1.0}) \times 10^{-4}$		–
$\quad\pi^-\ell^+\nu_\ell$		$(1.8 \pm 0.6) \times 10^{-4}$		–

Inclusive modes

K^+ anything		(78 ± 80) %		–

D, D^*, or D_s modes

$D^-\pi^+$		$(3.0 \pm 0.4) \times 10^{-3}$		2306
$D^-\rho^+$		$(7.9 \pm 1.4) \times 10^{-3}$		2236
$\overline{D}^0\pi^+\pi^-$		$< 1.6 \times 10^{-3}$	CL=90%	2301
$\quad D^*(2010)^-\pi^+$		$(2.76 \pm 0.21) \times 10^{-3}$		2254
$D^-\pi^+\pi^+\pi^-$		$(8.0 \pm 2.5) \times 10^{-3}$		2287
$\quad(D^-\pi^+\pi^+\pi^-)$ nonresonant		$(3.9 \pm 1.9) \times 10^{-3}$		2287
$\quad D^-\pi^+\rho^0$		$(1.1 \pm 1.0) \times 10^{-3}$		2207
$\qquad D^-a_1(1260)^+$		$(6.0 \pm 3.3) \times 10^{-3}$		2121
$D^*(2010)^-\pi^+\pi^0$		(1.5 ± 0.5) %		2247
$\quad D^*(2010)^-\rho^+$		$(6.7 \pm 3.3) \times 10^{-3}$		2181
$D^*(2010)^-\pi^+\pi^+\pi^-$		$(7.6 \pm 1.7) \times 10^{-3}$	S=1.3	2235
$\quad(D^*(2010)^-\pi^+\pi^+\pi^-)$ non-resonant		$(0.0 \pm 2.5) \times 10^{-3}$		2235
$\quad D^*(2010)^-\pi^+\rho^0$		$(5.7 \pm 3.1) \times 10^{-3}$		2151
$\qquad D^*(2010)^-a_1(1260)^+$		(1.30 ± 0.27) %		2061
$D^*(2010)^-\pi^+\pi^+\pi^-\pi^0$		(3.4 ± 1.8) %		2218
$\overline{D}_2^*(2460)^-\pi^+$		$< 2.2 \times 10^{-3}$	CL=90%	2064
$\overline{D}_2^*(2460)^-\rho^+$		$< 4.9 \times 10^{-3}$	CL=90%	1979
$D^-D_s^+$		$(8.0 \pm 3.0) \times 10^{-3}$		1812
$D^*(2010)^-D_s^+$		$(9.6 \pm 3.4) \times 10^{-3}$		1735
$D^-D_s^{*+}$		(1.0 ± 0.5) %		1731
$D^*(2010)^-D_s^{*+}$		(2.0 ± 0.7) %		1649
$D_s^+\pi^-$		$< 2.8 \times 10^{-4}$	CL=90%	2270
$D_s^{*+}\pi^-$		$< 5 \times 10^{-4}$	CL=90%	2214
$D_s^+\rho^-$		$< 7 \times 10^{-4}$	CL=90%	2198
$D_s^{*+}\rho^-$		$< 8 \times 10^{-4}$	CL=90%	2139
$D_s^+a_1(1260)^-$		$< 2.6 \times 10^{-3}$	CL=90%	2079
$D_s^{*+}a_1(1260)^-$		$< 2.2 \times 10^{-3}$	CL=90%	2014
$D_s^-K^+$		$< 2.4 \times 10^{-4}$	CL=90%	2242
$D_s^{*-}K^+$		$< 1.7 \times 10^{-4}$	CL=90%	2185
$D_s^-K^*(892)^+$		$< 9.9 \times 10^{-4}$	CL=90%	2172
$D_s^{*-}K^*(892)^+$		$< 1.1 \times 10^{-3}$	CL=90%	2112
$D_s^-\pi^+K^0$		$< 5 \times 10^{-3}$	CL=90%	2221
$D_s^{*-}\pi^+K^0$		$< 3.1 \times 10^{-3}$	CL=90%	2164
$D_s^-\pi^+K^*(892)^0$		$< 4 \times 10^{-3}$	CL=90%	2136
$D_s^{*-}\pi^+K^*(892)^0$		$< 2.0 \times 10^{-3}$	CL=90%	2074
$\overline{D}^0\pi^0$		$< 1.2 \times 10^{-4}$	CL=90%	2308
$\overline{D}^0\rho^0$		$< 3.9 \times 10^{-4}$	CL=90%	2238
$\overline{D}^0\eta$		$< 1.3 \times 10^{-4}$	CL=90%	2274
$\overline{D}^0\eta'$		$< 9.4 \times 10^{-4}$	CL=90%	2198
$\overline{D}^0\omega$		$< 5.1 \times 10^{-4}$	CL=90%	2235
$\overline{D}^*(2007)^0\pi^0$		$< 4.4 \times 10^{-4}$	CL=90%	2256
$\overline{D}^*(2007)^0\rho^0$		$< 5.6 \times 10^{-4}$	CL=90%	2183
$\overline{D}^*(2007)^0\eta$		$< 2.6 \times 10^{-4}$	CL=90%	2220
$\overline{D}^*(2007)^0\eta'$		$< 1.4 \times 10^{-3}$	CL=90%	2141
$\overline{D}^*(2007)^0\omega$		$< 7.4 \times 10^{-4}$	CL=90%	2180
$D^*(2010)^+D^*(2010)^-$		$< 2.2 \times 10^{-3}$	CL=90%	1711
$D^*(2010)^+D^-$		$< 1.8 \times 10^{-3}$	CL=90%	1790
$D^+D^*(2010)^-$		$< 1.2 \times 10^{-3}$	CL=90%	1790

Charmonium modes

$J/\psi(1S)K^0$		$(8.9 \pm 1.2) \times 10^{-4}$		1683
$J/\psi(1S)K^+\pi^-$		$(1.1 \pm 0.6) \times 10^{-3}$		1652
$\quad J/\psi(1S)K^*(892)^0$		$(1.35 \pm 0.18) \times 10^{-3}$		1570
$J/\psi(1S)\pi^0$		$< 5.8 \times 10^{-5}$	CL=90%	1728
$J/\psi(1S)\eta$		$< 1.2 \times 10^{-3}$	CL=90%	1672
$J/\psi(1S)\rho^0$		$< 2.5 \times 10^{-4}$	CL=90%	1614

$J/\psi(1S)\omega$		$< 2.7 \times 10^{-4}$	CL=90%	1609
$\psi(2S)K^0$		$< 8 \times 10^{-4}$	CL=90%	1283
$\psi(2S)K^+\pi^-$		$< 1 \times 10^{-3}$	CL=90%	1238
$\psi(2S)K^*(892)^0$		$(1.4 \pm 0.9) \times 10^{-3}$		1113
$\chi_{c1}(1P)K^0$		$< 2.7 \times 10^{-3}$	CL=90%	1411
$\chi_{c1}(1P)K^*(892)^0$		$< 2.1 \times 10^{-3}$	CL=90%	1263

K or *K** modes

$K^+\pi^-$		$(1.5 {}^{+0.5}_{-0.4}) \times 10^{-5}$		2615
$K^0\pi^0$		$< 4.1 \times 10^{-5}$	CL=90%	2614
$\eta' K^0$		$(4.7 {}^{+2.8}_{-2.2}) \times 10^{-5}$		2528
$\eta' K^*(892)^0$		$< 3.9 \times 10^{-5}$	CL=90%	2472
$\eta K^*(892)^0$		$< 3.0 \times 10^{-5}$	CL=90%	2534
ηK^0		$< 3.3 \times 10^{-5}$	CL=90%	2593
K^+K^-		$< 4.3 \times 10^{-6}$	CL=90%	2593
$K^0\overline{K}^0$		$< 1.7 \times 10^{-5}$	CL=90%	2592
$K^+\rho^-$		$< 3.5 \times 10^{-5}$	CL=90%	2559
$K^0\rho^0$		$< 3.9 \times 10^{-5}$	CL=90%	2559
$K^0 f_0(980)$		$< 3.6 \times 10^{-4}$	CL=90%	2523
$K^*(892)^+\pi^-$		$< 7.2 \times 10^{-5}$	CL=90%	2562
$K^*(892)^0\pi^0$		$< 2.8 \times 10^{-5}$	CL=90%	2562
$K_2^*(1430)^+\pi^-$		$< 2.6 \times 10^{-3}$	CL=90%	2445
$K^0K^+K^-$		$< 1.3 \times 10^{-3}$	CL=90%	2522
$K^0\phi$		$< 8.8 \times 10^{-5}$	CL=90%	2516
$K^-\pi^+\pi^+\pi^-$	[*bbb*]	$< 2.3 \times 10^{-4}$	CL=90%	2600
$K^*(892)^0\pi^+\pi^-$		$< 1.4 \times 10^{-3}$	CL=90%	2556
$K^*(892)^0\rho^0$		$< 4.6 \times 10^{-4}$	CL=90%	2504
$K^*(892)^0 f_0(980)$		$< 1.7 \times 10^{-4}$	CL=90%	2467
$K_1(1400)^+\pi^-$		$< 1.1 \times 10^{-3}$	CL=90%	2451
$K^- a_1(1260)^+$	[*bbb*]	$< 2.3 \times 10^{-4}$	CL=90%	2471
$K^*(892)^0K^+K^-$		$< 6.1 \times 10^{-4}$	CL=90%	2466
$K^*(892)^0\phi$		$< 4.3 \times 10^{-5}$	CL=90%	2459
$K_1(1400)^0\rho^0$		$< 3.0 \times 10^{-3}$	CL=90%	2389
$K_1(1400)^0\phi$		$< 5.0 \times 10^{-3}$	CL=90%	2339
$K_2^*(1430)^0\rho^0$		$< 1.1 \times 10^{-3}$	CL=90%	2380
$K_2^*(1430)^0\phi$		$< 1.4 \times 10^{-3}$	CL=90%	2330
$K^*(892)^0\gamma$		$(4.0 \pm 1.9) \times 10^{-5}$		2564
$K_1(1270)^0\gamma$		$< 7.0 \times 10^{-3}$	CL=90%	2486
$K_1(1400)^0\gamma$		$< 4.3 \times 10^{-3}$	CL=90%	2453
$K_2^*(1430)^0\gamma$		$< 4.0 \times 10^{-4}$	CL=90%	2445
$K^*(1680)^0\gamma$		$< 2.0 \times 10^{-3}$	CL=90%	2361
$K_3^*(1780)^0\gamma$		< 1.0 %	CL=90%	2343
$K_4^*(2045)^0\gamma$		$< 4.3 \times 10^{-3}$	CL=90%	2244
$\phi\phi$		$< 3.9 \times 10^{-5}$	CL=90%	2435

Light unflavored meson modes

$\pi^+\pi^-$		$< 1.5 \times 10^{-5}$	CL=90%	2636
$\pi^0\pi^0$		$< 9.3 \times 10^{-6}$	CL=90%	2636
$\eta\pi^0$		$< 8 \times 10^{-6}$	CL=90%	2609
$\eta\eta$		$< 1.8 \times 10^{-5}$	CL=90%	2582
$\eta'\pi^0$		$< 1.1 \times 10^{-5}$	CL=90%	2551
$\eta'\eta'$		$< 4.7 \times 10^{-5}$	CL=90%	2460
$\eta'\eta$		$< 2.7 \times 10^{-5}$	CL=90%	2522
$\eta'\rho^0$		$< 2.3 \times 10^{-5}$	CL=90%	2493
$\eta\rho^0$		$< 1.3 \times 10^{-5}$	CL=90%	2554
$\pi^+\pi^-\pi^0$		$< 7.2 \times 10^{-4}$	CL=90%	2631
$\rho^0\pi^0$		$< 2.4 \times 10^{-5}$	CL=90%	2582
$\rho^\mp\pi^\pm$	[*gg*]	$< 8.8 \times 10^{-5}$	CL=90%	2582
$\pi^+\pi^-\pi^+\pi^-$		$< 2.3 \times 10^{-4}$	CL=90%	2621
$\rho^0\rho^0$		$< 2.8 \times 10^{-4}$	CL=90%	2525
$a_1(1260)^\mp\pi^\pm$	[*gg*]	$< 4.9 \times 10^{-4}$	CL=90%	2494
$a_2(1320)^\mp\pi^\pm$	[*gg*]	$< 3.0 \times 10^{-4}$	CL=90%	2473
$\pi^+\pi^-\pi^0\pi^0$		$< 3.1 \times 10^{-3}$	CL=90%	2622
$\rho^+\rho^-$		$< 2.2 \times 10^{-3}$	CL=90%	2525
$a_1(1260)^0\pi^0$		$< 1.1 \times 10^{-3}$	CL=90%	2494
$\omega\pi^0$		$< 4.6 \times 10^{-4}$	CL=90%	2580
$\pi^+\pi^+\pi^-\pi^-\pi^0$		$< 9.0 \times 10^{-3}$	CL=90%	2609
$a_1(1260)^+\rho^-$		$< 3.4 \times 10^{-3}$	CL=90%	2434
$a_1(1260)^0\rho^0$		$< 2.4 \times 10^{-3}$	CL=90%	2434
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$		$< 3.0 \times 10^{-3}$	CL=90%	2592
$a_1(1260)^+a_1(1260)^-$		$< 2.8 \times 10^{-3}$	CL=90%	2336
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$		< 1.1 %	CL=90%	2572

Baryon modes

$p\overline{p}$		$< 1.8 \times 10^{-5}$	CL=90%	2467
$p\overline{p}\pi^+\pi^-$		$< 2.5 \times 10^{-4}$	CL=90%	2406
$p\overline{\Lambda}\pi^-$		$< 1.8 \times 10^{-4}$	CL=90%	2401
$\Delta^0\overline{\Delta}^0$		$< 1.5 \times 10^{-3}$	CL=90%	2334
$\Delta^{++}\Delta^{--}$		$< 1.1 \times 10^{-4}$	CL=90%	2334
$\overline{\Sigma}_c^{--}\Delta^{++}$		$< 1.0 \times 10^{-3}$	CL=90%	1839
$\Lambda_c^- p\pi^+\pi^-$		$(1.3 \pm 0.6) \times 10^{-3}$		–
$\Lambda_c^- p$		$< 2.1 \times 10^{-4}$	CL=90%	2021
$\Lambda_c^- p\pi^0$		$< 5.9 \times 10^{-4}$	CL=90%	–
$\Lambda_c^- p\pi^+\pi^-\pi^0$		$< 5.07 \times 10^{-3}$	CL=90%	–
$\Lambda_c^- p\pi^+\pi^-\pi^+\pi^-$		$< 2.74 \times 10^{-3}$	CL=90%	–

Lepton Family number (*LF*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

$\gamma\gamma$	*B1*		$< 3.9 \times 10^{-5}$	CL=90%	2640
e^+e^-	*B1*		$< 5.9 \times 10^{-6}$	CL=90%	2640
$\mu^+\mu^-$	*B1*		$< 6.8 \times 10^{-7}$	CL=90%	2637
$K^0e^+e^-$	*B1*		$< 3.0 \times 10^{-4}$	CL=90%	2616
$K^0\mu^+\mu^-$	*B1*		$< 3.6 \times 10^{-4}$	CL=90%	2612
$K^*(892)^0e^+e^-$	*B1*		$< 2.9 \times 10^{-4}$	CL=90%	2564
$K^*(892)^0\mu^+\mu^-$	*B1*		$< 2.3 \times 10^{-5}$	CL=90%	2559
$K^*(892)^0\nu\overline{\nu}$	*B1*		$< 1.0 \times 10^{-3}$	CL=90%	2244
$e^\pm\mu^\mp$	*LF*	[*gg*]	$< 5.9 \times 10^{-6}$	CL=90%	2639
$e^\pm\tau^\mp$	*LF*	[*gg*]	$< 5.3 \times 10^{-4}$	CL=90%	2341
$\mu^\pm\tau^\mp$	*LF*	[*gg*]	$< 8.3 \times 10^{-4}$	CL=90%	2339

$B^\pm/B^0$ ADMIXTURE

The branching fraction measurements are for an admixture of B mesons at the $\Upsilon(4S)$. The values quoted assume that $B(\Upsilon(4S) \to B\overline{B}) = 100\%$.

For inclusive branching fractions, *e.g.*, $B \to D^\pm$ anything, the treatment of multiple D's in the final state must be defined. One possiblity would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

$\overline{B}$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing.

***B* DECAY MODES**		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$B \to e^+\nu_e$ anything	[*ccc*]	(10.41 ± 0.29) %	S=1.2	–
$B \to \overline{p}e^+\nu_e$ anything		$< 1.6 \times 10^{-3}$	CL=90%	–
$B \to \mu^+\nu_\mu$ anything	[*ccc*]	(10.3 ± 0.5) %		–
$B \to \ell^+\nu_\ell$ anything	[*pp,ccc*]	(10.45 ± 0.21) %		–
$B \to D^-\ell^+\nu_\ell$ anything	[*pp*]	(2.7 ± 0.8) %		–
$B \to \overline{D}^0\ell^+\nu_\ell$ anything	[*pp*]	(7.0 ± 1.4) %		–
$B \to \overline{D}^{**}\ell^+\nu_\ell$	[*pp,ddd*]	(2.7 ± 0.7) %		–
$B \to \overline{D}_1(2420)\ell^+\nu_\ell$ anything		$(7.4 \pm 1.6) \times 10^{-3}$		–
$B \to D\pi\ell^+\nu_\ell$ anything + $D^*\pi\ell^+\nu_\ell$ anything		(2.3 ± 0.4) %		–
$B \to \overline{D}_2^*(2460)\ell^+\nu_\ell$ anything		$< 6.5 \times 10^{-3}$	CL=95%	–
$B \to D^{*-}\pi^+\ell^+\nu_\ell$ anything		(1.00 ± 0.34) %		–
$B \to D_s^-\ell^+\nu_\ell$ anything	[*pp*]	$< 9 \times 10^{-3}$	CL=90%	–
$B \to D_s^-\ell^+\nu_\ell K^+$ anything	[*pp*]	$< 6 \times 10^{-3}$	CL=90%	–
$B \to D_s^-\ell^+\nu_\ell K^0$ anything	[*pp*]	$< 9 \times 10^{-3}$	CL=90%	–
$B \to K^+\ell^+\nu_\ell$ anything	[*pp*]	(6.0 ± 0.5) %		–
$B \to K^-\ell^+\nu_\ell$ anything	[*pp*]	$(10 \pm 4) \times 10^{-3}$		–
$B \to K^0/\overline{K}^0\ell^+\nu_\ell$ anything	[*pp*]	(4.4 ± 0.5) %		–

D, D^*, or D_s modes

$B \to D^\pm$ anything		(24.1 ±1.9) %		–
$B \to D^0/\overline{D}^0$ anything		(63.1 ±2.9) %	S=1.1	–
$B \to D^*(2010)^\pm$ anything		(22.7 ±1.6) %		–
$B \to D^*(2007)^0$ anything		(26.0 ±2.7) %		–
$B \to D_s^\pm$ anything	[gg]	(10.0 ±2.5) %		–
$b \to c\overline{c}s$		(22 ±4) %		–
$B \to D_s D$, $D_s^* D$, $D_s D^*$, or $D_s^* D^*$	[gg]	(4.9 ±1.3) %		–
$B \to D^*(2010)\gamma$		< 1.1 × 10^{-3}	CL=90%	–
$B \to D_s^+ \pi^-$, $D_s^{*+} \pi^-$, $D_s^+ \rho^-$, $D_s^{*+} \rho^-$, $D_s^+ \pi^0$, $D_s^{*+} \pi^0$, $D_s^+ \eta$, $D_s^{*+} \eta$, $D_s^+ \rho^0$, $D_s^{*+} \rho^0$, $D_s^+ \omega$, $D_s^{*+} \omega$	[gg]	< 5 × 10^{-4}	CL=90%	–
$B \to D_{s1}(2536)^+$ anything		< 9.5 × 10^{-3}	CL=90%	–

Charmonium modes

$B \to J/\psi(1S)$ anything		(1.13±0.06) %		–
$B \to J/\psi(1S)$ (direct) anything		(8.0 ±0.8) × 10^{-3}		–
$B \to \psi(2S)$ anything		(3.5 ±0.5) × 10^{-3}		–
$B \to \chi_{c1}(1P)$ anything		(4.2 ±0.7) × 10^{-3}		–
$B \to \chi_{c1}(1P)$ (direct) anything		(3.7 ±0.7) × 10^{-3}		–
$B \to \chi_{c2}(1P)$ anything		< 3.8 × 10^{-3}	CL=90%	–
$B \to \eta_c(1S)$ anything		< 9 × 10^{-3}	CL=90%	–

K or K^* modes

$B \to K^\pm$ anything	[gg]	(78.9 ±2.5) %		–
$B \to K^+$ anything		(66 ±5) %		–
$B \to K^-$ anything		(13 ±4) %		–
$B \to K^0/\overline{K}^0$ anything	[gg]	(64 ±4) %		–
$B \to K^*(892)^\pm$ anything		(18 ±6) %		–
$B \to K^*(892)^0/\overline{K}^*(892)^0$ anything	[gg]	(14.6 ±2.6) %		–
$B \to K_1(1400)\gamma$		< 4.1 × 10^{-4}	CL=90%	–
$B \to K_2^*(1430)\gamma$		< 8.3 × 10^{-4}	CL=90%	–
$B \to K_2(1770)\gamma$		< 1.2 × 10^{-3}	CL=90%	–
$B \to K_3^*(1780)\gamma$		< 3.0 × 10^{-3}	CL=90%	–
$B \to K_4^*(2045)\gamma$		< 1.0 × 10^{-3}	CL=90%	–
$B \to \overline{b} \to \overline{s}\gamma$		(2.3 ±0.7) × 10^{-4}		–
$B \to \overline{b} \to \overline{s}$gluon		< 6.8 %	CL=90%	–

Light unflavored meson modes

$B \to \pi^\pm$ anything	[gg,eee]	(359 ±7) %		–
$B \to \eta$ anything		(17.6 ±1.6) %		–
$B \to \rho^0$ anything		(21 ±5) %		–
$B \to \omega$ anything		< 81 %	CL=90%	–
$B \to \phi$ anything		(3.5 ±0.7) %	S=1.8	–

Baryon modes

$B \to \Lambda_c^\pm$ anything		(6.4 ±1.1) %		–
$B \to \Lambda_c^- e^+$ anything		< 3.2 × 10^{-3}	CL=90%	–
$B \to \Lambda_c^- p$anything		(3.6 ±0.7) %		–
$B \to \Lambda_c^- p e^+ \nu_e$		< 1.5 × 10^{-3}	CL=90%	–
$B \to \overline{\Sigma}_c^{--}$ anything		(4.2 ±2.4) × 10^{-3}		–
$B \to \overline{\Sigma}_c^{-}$ anything		< 9.6 × 10^{-3}	CL=90%	–
$B \to \overline{\Sigma}_c^{0}$ anything		(4.6 ±2.4) × 10^{-3}		–
$B \to \overline{\Sigma}_c^{0} N (N = p$ or $n)$		< 1.5 × 10^{-3}	CL=90%	–
$B \to \Xi_c^0$ anything × B($\Xi_c^0 \to \Xi^- \pi^+$)		(1.4 ±0.5) × 10^{-4}		–
$B \to \Xi_c^+$ anything × B($\Xi_c^+ \to \Xi^- \pi^+ \pi^+$)		(4.5 $^{+1.3}_{-1.2}$) × 10^{-4}		–
$B \to p/\overline{p}$anything	[gg]	(8.0 ±0.4) %		–
$B \to p/\overline{p}$(direct) anything	[gg]	(5.5 ±0.5) %		–
$B \to \Lambda/\overline{\Lambda}$anything	[gg]	(4.0 ±0.5) %		–
$B \to \Xi^-/\overline{\Xi}^+$anything	[gg]	(2.7 ±0.6) × 10^{-3}		–
$B \to$ baryons anything		(6.8 ±0.6) %		–
$B \to p\overline{p}$anything		(2.47±0.23) %		–
$B \to \Lambda\overline{p}/\overline{\Lambda}p$anything	[gg]	(2.5 ±0.4) %		–
$B \to \Lambda\overline{\Lambda}$anything		< 5 × 10^{-3}	CL=90%	–

Lepton Family number (LF) violating modes or $\Delta B = 1$ weak neutral current ($B1$) modes

$B \to e^+ e^- s$	$B1$	< 5.7 × 10^{-5}	CL=90%	–
$B \to \mu^+ \mu^- s$	$B1$	< 5.8 × 10^{-5}	CL=90%	–
$B \to e^\pm \mu^\mp s$	LF	< 2.2 × 10^{-5}	CL=90%	–

$B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE

These measurements are for an admixture of bottom particles at high energy (LEP, Tevatron, $Sp\overline{p}S$).

Mean life $\tau = (1.564 \pm 0.014) \times 10^{-12}$ s

Mean life $\tau = (1.72 \pm 0.10) \times 10^{-12}$ s Charged b-hadron admixture

Mean life $\tau = (1.58 \pm 0.14) \times 10^{-12}$ s Neutral b-hadron admixture

$\tau_{\text{charged } b\text{-hadron}}/\tau_{\text{neutral } b\text{-hadron}} = 1.09 \pm 0.13$

The branching fraction measurements are for an admixture of B mesons and baryons at energies above the $\Upsilon(4S)$. Only the highest energy results (LEP, Tevatron, $Sp\overline{p}S$) are used in the branching fraction averages. The production fractions give our best current estimate of the admixture at LEP.

For inclusive branching fractions, *e.g.*, $B \to D^\pm$ anything, the treatment of multiple D's in the final state must be defined. One possiblity would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

The modes below are listed for a $\overline{b}$ initial state. b modes are their charge conjugates. Reactions indicate the weak decay vertex and do not include mixing.

$\overline{b}$ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)

PRODUCTION FRACTIONS

The production fractions for weakly decaying b-hadrons at the Z have been calculated from the best values of mean lives, mixing parameters, and branching fractions in this edition by the LEP B Oscillation Working Group as described in the note "Production and Decay of b-Flavored Hadrons" in the $B^\pm$ Particle Listings. Values assume

$$\mathrm{B}(\overline{b} \to B^+) = \mathrm{B}(\overline{b} \to B^0)$$
$$\mathrm{B}(\overline{b} \to B^+) + \mathrm{B}(\overline{b} \to B^0) + \mathrm{B}(\overline{b} \to B_s^0) + \mathrm{B}(b \to \Lambda_b) = 100\ \%.$$

The notation for production fractions varies in the literature (f_{B^0}, $f(b \to \overline{B}^0)$, $\mathrm{Br}(b \to \overline{B}^0)$). We use our own branching fraction notation here, $\mathrm{B}(\overline{b} \to B^0)$.

B^+		(39.7 $^{+1.8}_{-2.2}$) %		–
B^0		(39.7 $^{+1.8}_{-2.2}$) %		–
B_s^0		(10.5 $^{+1.8}_{-1.7}$) %		–
Λ_b		(10.1 $^{+3.9}_{-3.1}$) %		–

DECAY MODES

Semileptonic and leptonic modes

ν anything		(23.1 ± 1.5) %		–
$\ell^+ \nu_\ell$ anything	[pp,ccc]	(10.99± 0.23) %		–
$e^+ \nu_e$ anything	[ccc]	(10.9 ± 0.5) %		–
$\mu^+ \nu_\mu$ anything	[ccc]	(10.8 ± 0.5) %		–
$D^- \ell^+ \nu_\ell$ anything	[pp]	(2.02± 0.29) %		–
$\overline{D}^0 \ell^+ \nu_\ell$ anything	[pp]	(6.5 ± 0.6) %		–
$D^{*-} \ell^+ \nu_\ell$ anything	[pp]	(2.76± 0.29) %		–
$\overline{D}_j^0 \ell^+ \nu_\ell$ anything	[pp,fff]	seen		–
$D_j^- \ell^+ \nu_\ell$ anything	[pp,fff]	seen		–
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$ anything		seen		–
$D_2^*(2460)^- \ell^+ \nu_\ell$ anything		seen		–
$\tau^+ \nu_\tau$ anything		(2.6 ± 0.4) %		–
$\overline{c} \to \ell^- \overline{\nu}_\ell$ anything	[pp]	(7.8 ± 0.6) %		–

		Charmed meson and baryon modes		
$\overline{D}^0$ anything		(60.1 ± 3.2) %		–
D^- anything		(23.7 ± 2.3) %		–
$\overline{D}_s$ anything		(18 ± 5) %		–
Λ_c anything		(9.7 ± 2.9) %		–
$\overline{c}/c$ anything	[eee]	(117 ± 4) %		–
		Charmonium modes		
$J/\psi(1S)$ anything		(1.16 ± 0.10) %		–
$\psi(2S)$ anything		$(4.8 \pm 2.4) \times 10^{-3}$		–
$\chi_{c1}(1P)$ anything		(1.8 ± 0.5) %		–
		K or K^* modes		
$\overline{s}\gamma$		$< 5.4 \times 10^{-4}$	90%	–
$K^\pm$ anything		(88 ± 19) %		–
K^0_S anything		(29.0 ± 2.9) %		–
		Pion modes		
π^0 anything	[eee]	(278 ± 60) %		–
		Baryon modes		
$p/\overline{p}$ anything		(14 ± 6) %		–
		Other modes		
charged anything	[eee]	(497 ± 7) %		–
hadron$^+$ hadron$^-$		$(1.7 {}^{+1.0}_{-0.7}) \times 10^{-5}$		–
charmless		$(7 \pm 21) \times 10^{-3}$		–
		Baryon modes		
$\Lambda/\overline{\Lambda}$ anything		(5.9 ± 0.6) %		–
		$\Delta B = 1$ weak neutral current ($B1$) modes		
$\mu^+\mu^-$ anything	$B1$	$< 3.2 \times 10^{-4}$	90%	–

$\boxed{B^*}$

$I(J^P) = \frac{1}{2}(1^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^*} = 5324.9 \pm 1.8$ MeV

$m_{B^*} - m_B = 45.78 \pm 0.35$ MeV

B^* DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$B\gamma$	dominant	46

BOTTOM, STRANGE MESONS
($B = \pm1, S = \mp1$)

$B^0_s = s\overline{b}$, $\overline{B}^0_s = \overline{s}\,b$, similarly for B^*_s's

$\boxed{B^0_s}$

$I(J^P) = 0(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0_s} = 5369.3 \pm 2.0$ MeV

Mean life $\tau = (1.54 \pm 0.07) \times 10^{-12}$ s

$c\tau = 462\ \mu$m

B^0_s-$\overline{B}^0_s$ mixing parameters

χ_B at high energy $= f_d\chi_d + f_s\chi_s = 0.118 \pm 0.006$

$\Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}} > 9.1 \times 10^{12}\ \hbar\ s^{-1}$, CL = 95%

$x_s = \Delta m_{B^0_s}/\Gamma_{B^0_s} > 14.0$, CL = 95%

$\chi_s > 0.4975$, CL = 95%

These branching fractions all scale with $B(\overline{b} \to B^0_s)$, the LEP B^0_s production fraction. The first four were evaluated using $B(\overline{b} \to B^0_s) = (10.5^{+1.8}_{-1.7})\%$ and the rest assume $B(\overline{b} \to B^0_s) = 12\%$.

The branching fraction $B(B^0_s \to D^-_s \ell^+ \nu_\ell\,\text{anything})$ is not a pure measurement since the measured product branching fraction $B(\overline{b} \to B^0_s) \times B(B^0_s \to D^-_s \ell^+ \nu_\ell\,\text{anything})$ was used to determine $B(\overline{b} \to B^0_s)$, as described in the note on "Production and Decay of b-Flavored Hadrons."

B^0_s DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
D^-_s anything		(92 ± 33) %		–
$D^-_s \ell^+ \nu_\ell$ anything	[ggg]	(8.1 ± 2.5) %		–
$D^-_s \pi^+$		< 13 %		2321
$J/\psi(1S)\phi$		$(9.3 \pm 3.3) \times 10^{-4}$		1590
$J/\psi(1S)\pi^0$		$< 1.2 \times 10^{-3}$	90%	1788
$J/\psi(1S)\eta$		$< 3.8 \times 10^{-3}$	90%	1735
$\psi(2S)\phi$		seen		1122
$\pi^+\pi^-$		$< 1.7 \times 10^{-4}$	90%	1122
$\pi^0\pi^0$		$< 2.1 \times 10^{-4}$	90%	2861
$\eta\pi^0$		$< 1.0 \times 10^{-3}$	90%	2655
$\eta\eta$		$< 1.5 \times 10^{-3}$	90%	2628
π^+K^-		$< 2.1 \times 10^{-4}$	90%	2660
K^+K^-		$< 5.9 \times 10^{-5}$	90%	2639
$p\overline{p}$		$< 5.9 \times 10^{-5}$	90%	2515
$\gamma\gamma$		$< 1.48 \times 10^{-4}$	90%	2685
$\phi\gamma$		$< 7 \times 10^{-4}$	90%	2588
		Lepton Family number (LF) violating modes or $\Delta B = 1$ weak neutral current ($B1$) modes		
$\mu^+\mu^-$	$B1$	$< 2.0 \times 10^{-6}$	90%	2682
e^+e^-	$B1$	$< 5.4 \times 10^{-5}$	90%	2864
$e^\pm\mu^\mp$	LF [gg]	$< 4.1 \times 10^{-5}$	90%	2864
$\phi\nu\overline{\nu}$	$B1$	$< 5.4 \times 10^{-3}$	90%	–

$c\overline{c}$ MESONS

$\eta_c(1S)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 2979.8 \pm 2.1$ MeV (S = 2.1)
Full width $\Gamma = 13.2^{+3.8}_{-3.2}$ MeV

$\eta_c(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Decays involving hadronic resonances			
$\eta'(958)\pi\pi$	(4.1 ± 1.7) %		1319
$\rho\rho$	(2.6 ± 0.9) %		1275
$K^*(892)^0 K^- \pi^+ +$ c.c.	(2.0 ± 0.7) %		1273
$K^*(892)\overline{K}^*(892)$	$(8.5 \pm 3.1) \times 10^{-3}$		1193
$\phi\phi$	$(7.1 \pm 2.8) \times 10^{-3}$		1086
$a_0(980)\pi$	< 2 %	90%	1323
$a_2(1320)\pi$	< 2 %	90%	1193
$K^*(892)\overline{K} +$ c.c.	< 1.28 %	90%	1307
$f_2(1270)\eta$	< 1.1 %	90%	1142
$\omega\omega$	$< 3.1 \times 10^{-3}$	90%	1268
Decays into stable hadrons			
$K\overline{K}\pi$	(5.5 ± 1.7) %		1378
$\eta\pi\pi$	(4.9 ± 1.8) %		1425
$\pi^+\pi^- K^+ K^-$	$(2.0\ ^{+0.7}_{-0.6})$ %		1342
$2(K^+ K^-)$	(2.1 ± 1.2) %		1053
$2(\pi^+\pi^-)$	(1.2 ± 0.4) %		1457
$p\overline{p}$	$(1.2 \pm 0.4) \times 10^{-3}$		1157
$K\overline{K}\eta$	< 3.1 %	90%	1262
$\pi^+\pi^- p\overline{p}$	< 1.2 %	90%	1023
$\Lambda\overline{\Lambda}$	$< 2 \times 10^{-3}$	90%	987
Radiative decays			
$\gamma\gamma$	$(3.0 \pm 1.2) \times 10^{-4}$		1489

$J/\psi(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.88 \pm 0.04$ MeV
Full width $\Gamma = 87 \pm 5$ keV
$\Gamma_{ee} = 5.26 \pm 0.37$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons		(87.7 ± 0.5) %		–
virtual $\gamma \rightarrow$ hadrons		(17.0 ± 2.0) %		–
$e^+ e^-$		(6.02 ± 0.19) %		1548
$\mu^+ \mu^-$		(6.01 ± 0.19) %		1545
Decays involving hadronic resonances				
$\rho\pi$		(1.27 ± 0.09) %		1449
$\rho^0\pi^0$		$(4.2 \pm 0.5) \times 10^{-3}$		1449
$a_2(1320)\rho$		(1.09 ± 0.22) %		1125
$\omega\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$		1392
$\omega\pi^+\pi^-$		$(7.2 \pm 1.0) \times 10^{-3}$		1435
$\omega f_2(1270)$		$(4.3 \pm 0.6) \times 10^{-3}$		1143
$K^*(892)^0 \overline{K}{}_2^*(1430)^0 +$ c.c.		$(6.7 \pm 2.6) \times 10^{-3}$		1005
$\omega K^*(892)\overline{K} +$ c.c.		$(5.3 \pm 2.0) \times 10^{-3}$		1098
$K^+ \overline{K}^*(892)^- +$ c.c.		$(5.0 \pm 0.4) \times 10^{-3}$		1373
$K^0 \overline{K}^*(892)^0 +$ c.c.		$(4.2 \pm 0.4) \times 10^{-3}$		1371
$\omega\pi^0\pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$		1436
$b_1(1235)^{\pm}\pi^{\mp}$	[gg]	$(3.0 \pm 0.5) \times 10^{-3}$		1299
$\omega K^{\pm} K_S^0 \pi^{\mp}$	[gg]	$(3.0 \pm 0.7) \times 10^{-3}$		1210
$b_1(1235)^0\pi^0$		$(2.3 \pm 0.6) \times 10^{-3}$		1299
$\phi K^*(892)\overline{K} +$ c.c.		$(2.04 \pm 0.28) \times 10^{-3}$		969
$\omega K\overline{K}$		$(1.9 \pm 0.4) \times 10^{-3}$		1268
$\omega f_J(1710) \rightarrow \omega K\overline{K}$		$(4.8 \pm 1.1) \times 10^{-4}$		878
$\phi 2(\pi^+\pi^-)$		$(1.60 \pm 0.32) \times 10^{-3}$		1318
$\Delta(1232)^{++}\overline{p}\pi^-$		$(1.6 \pm 0.5) \times 10^{-3}$		1030
$\omega\eta$		$(1.58 \pm 0.16) \times 10^{-3}$		1394
$\phi K\overline{K}$		$(1.48 \pm 0.22) \times 10^{-3}$		1179
$\phi f_J(1710) \rightarrow \phi K\overline{K}$		$(3.6 \pm 0.6) \times 10^{-4}$		875
$p\overline{p}\omega$		$(1.30 \pm 0.25) \times 10^{-3}$	S=1.3	769
$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		$(1.10 \pm 0.29) \times 10^{-3}$		938
$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[gg]	$(1.03 \pm 0.13) \times 10^{-3}$		692
$p\overline{p}\eta'(958)$		$(9 \pm 4) \times 10^{-4}$	S=1.7	596
$\phi f'_2(1525)$		$(8 \pm 4) \times 10^{-4}$	S=2.7	871
$\phi\pi^+\pi^-$		$(8.0 \pm 1.2) \times 10^{-4}$		1365
$\phi K^{\pm} K_S^0 \pi^{\mp}$	[gg]	$(7.2 \pm 0.9) \times 10^{-4}$		1114
$\omega f_1(1420)$		$(6.8 \pm 2.4) \times 10^{-4}$		1062
$\phi\eta$		$(6.5 \pm 0.7) \times 10^{-4}$		1320
$\Xi(1530)^-\overline{\Xi}^+$		$(5.9 \pm 1.5) \times 10^{-4}$		597
$pK^-\overline{\Sigma}(1385)^0$		$(5.1 \pm 3.2) \times 10^{-4}$		645
$\omega\pi^0$		$(4.2 \pm 0.6) \times 10^{-4}$	S=1.4	1447
$\phi\eta'(958)$		$(3.3 \pm 0.4) \times 10^{-4}$		1192
$\phi f_0(980)$		$(3.2 \pm 0.9) \times 10^{-4}$	S=1.9	1182
$\Xi(1530)^0\overline{\Xi}^0$		$(3.2 \pm 1.4) \times 10^{-4}$		608
$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[gg]	$(3.1 \pm 0.5) \times 10^{-4}$		857
$\phi f_1(1285)$		$(2.6 \pm 0.5) \times 10^{-4}$	S=1.1	1032
$\rho\eta$		$(1.93 \pm 0.23) \times 10^{-4}$		1398
$\omega\eta'(958)$		$(1.67 \pm 0.25) \times 10^{-4}$		1279
$\omega f_0(980)$		$(1.4 \pm 0.5) \times 10^{-4}$		1271
$\rho\eta'(958)$		$(1.05 \pm 0.18) \times 10^{-4}$		1283
$p\overline{p}\phi$		$(4.5 \pm 1.5) \times 10^{-5}$		527
$a_2(1320)^{\pm}\pi^{\mp}$	[gg]	$< 4.3 \times 10^{-3}$	CL=90%	1263
$K\overline{K}{}_2^*(1430) +$ c.c.		$< 4.0 \times 10^{-3}$	CL=90%	1159
$K_2^*(1430)^0\overline{K}{}_2^*(1430)^0$		$< 2.9 \times 10^{-3}$	CL=90%	588
$K^*(892)^0\overline{K}^*(892)^0$		$< 5 \times 10^{-4}$	CL=90%	1263
$\phi f_2(1270)$		$< 3.7 \times 10^{-4}$	CL=90%	1036
$p\overline{p}\rho$		$< 3.1 \times 10^{-4}$	CL=90%	779
$\phi\eta(1440) \rightarrow \phi\eta\pi\pi$		$< 2.5 \times 10^{-4}$	CL=90%	946
$\omega f'_2(1525)$		$< 2.2 \times 10^{-4}$	CL=90%	1003
$\Sigma(1385)^0\overline{\Lambda}$		$< 2 \times 10^{-4}$	CL=90%	911
$\Delta(1232)^+\overline{p}$		$< 1 \times 10^{-4}$	CL=90%	1100
$\Sigma^0\overline{\Lambda}$		$< 9 \times 10^{-5}$	CL=90%	1032
$\phi\pi^0$		$< 6.8 \times 10^{-6}$	CL=90%	1377
Decays into stable hadrons				
$2(\pi^+\pi^-)\pi^0$		(3.37 ± 0.26) %		1496
$3(\pi^+\pi^-)\pi^0$		(2.9 ± 0.6) %		1433
$\pi^+\pi^-\pi^0$		(1.50 ± 0.20) %		1533
$\pi^+\pi^-\pi^0 K^+ K^-$		(1.20 ± 0.30) %		1368
$4(\pi^+\pi^-)\pi^0$		$(9.0 \pm 3.0) \times 10^{-3}$		1345
$\pi^+\pi^- K^+ K^-$		$(7.2 \pm 2.3) \times 10^{-3}$		1407
$K\overline{K}\pi$		$(6.1 \pm 1.0) \times 10^{-3}$		1440
$p\overline{p}\pi^+\pi^-$		$(6.0 \pm 0.5) \times 10^{-3}$	S=1.3	1107
$2(\pi^+\pi^-)$		$(4.0 \pm 1.0) \times 10^{-3}$		1517
$3(\pi^+\pi^-)$		$(4.0 \pm 2.0) \times 10^{-3}$		1466
$n\overline{n}\pi^+\pi^-$		$(4 \pm 4) \times 10^{-3}$		1106
$\Sigma^0\overline{\Sigma}^0$		$(1.27 \pm 0.17) \times 10^{-3}$		992
$2(\pi^+\pi^-)K^+K^-$		$(3.1 \pm 1.3) \times 10^{-3}$		1320
$p\overline{p}\pi^+\pi^-\pi^0$	[hhh]	$(2.3 \pm 0.9) \times 10^{-3}$	S=1.9	1033
$p\overline{p}$		$(2.14 \pm 0.10) \times 10^{-3}$		1232
$p\overline{p}\eta$		$(2.09 \pm 0.18) \times 10^{-3}$		948
$p\overline{n}\pi^-$		$(2.00 \pm 0.10) \times 10^{-3}$		1174
$n\overline{n}$		$(1.9 \pm 0.5) \times 10^{-3}$		1231
$\Xi\overline{\Xi}$		$(1.8 \pm 0.4) \times 10^{-3}$	S=1.8	818
$\Lambda\overline{\Lambda}$		$(1.35 \pm 0.14) \times 10^{-3}$	S=1.2	1074
$p\overline{p}\pi^0$		$(1.09 \pm 0.09) \times 10^{-3}$		1176
$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[gg]	$(1.06 \pm 0.12) \times 10^{-3}$		945
$pK^-\overline{\Lambda}$		$(8.9 \pm 1.6) \times 10^{-4}$		876
$2(K^+K^-)$		$(7.0 \pm 3.0) \times 10^{-4}$		1131
$pK^-\overline{\Sigma}^0$		$(2.9 \pm 0.8) \times 10^{-4}$		820
K^+K^-		$(2.37 \pm 0.31) \times 10^{-4}$		1468
$\Lambda\overline{\Lambda}\pi^0$		$(2.2 \pm 0.7) \times 10^{-4}$		998
$\pi^+\pi^-$		$(1.47 \pm 0.23) \times 10^{-4}$		1542
$K_S^0 K_L^0$		$(1.08 \pm 0.14) \times 10^{-4}$		1466
$\Lambda\overline{\Sigma} +$ c.c.		$< 1.5 \times 10^{-4}$	CL=90%	1032
$K_S^0 K_S^0$		$< 5.2 \times 10^{-6}$	CL=90%	1466
Radiative decays				
$\gamma\eta_c(1S)$		(1.3 ± 0.4) %		116
$\gamma\pi^+\pi^- 2\pi^0$		$(8.3 \pm 3.1) \times 10^{-3}$		1518
$\gamma\eta\pi\pi$		$(6.1 \pm 1.0) \times 10^{-3}$		1487
$\gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi$	[p]	$(9.1 \pm 1.8) \times 10^{-4}$		1223
$\gamma\eta(1440) \rightarrow \gamma\gamma\rho^0$		$(6.4 \pm 1.4) \times 10^{-5}$		1223
$\gamma\eta(1440) \rightarrow \gamma\eta\pi^+\pi^-$		$(3.4 \pm 0.7) \times 10^{-4}$		–
$\gamma\rho\rho$		$(4.5 \pm 0.8) \times 10^{-3}$		1343
$\gamma\eta'(958)$		$(4.31 \pm 0.30) \times 10^{-3}$		1400
$\gamma 2\pi^+ 2\pi^-$		$(2.8 \pm 0.5) \times 10^{-3}$	S=1.9	1517
$\gamma f_4(2050)$		$(2.7 \pm 0.7) \times 10^{-3}$		874
$\gamma\omega\omega$		$(1.59 \pm 0.33) \times 10^{-3}$		1337
$\gamma\eta(1440) \rightarrow \gamma\rho^0\rho^0$		$(1.7 \pm 0.4) \times 10^{-3}$	S=1.3	1223
$\gamma f_2(1270)$		$(1.38 \pm 0.14) \times 10^{-3}$		1286
$\gamma f_J(1710) \rightarrow \gamma K\overline{K}$		$(8.5\ ^{+1.2}_{-0.9}) \times 10^{-4}$	S=1.2	1075

$\gamma\eta$	$(8.6 \pm 0.8) \times 10^{-4}$		1500
$\gamma f_1(1420) \rightarrow \gamma K\overline{K}\pi$	$(8.3 \pm 1.5) \times 10^{-4}$		1220
$\gamma f_1(1285)$	$(6.5 \pm 1.0) \times 10^{-4}$		1283
$\gamma f_2'(1525)$	$(4.7 {}^{+0.7}_{-0.5}) \times 10^{-4}$		1173
$\gamma\phi\phi$	$(4.0 \pm 1.2) \times 10^{-4}$	S=2.1	1166
$\gamma p\overline{p}$	$(3.8 \pm 1.0) \times 10^{-4}$		1232
$\gamma\eta(2225)$	$(2.9 \pm 0.6) \times 10^{-4}$		834
$\gamma\eta(1760) \rightarrow \gamma\rho^0\rho^0$	$(1.3 \pm 0.9) \times 10^{-4}$		1048
$\gamma\pi^0$	$(3.9 \pm 1.3) \times 10^{-5}$		1546
$\gamma p\overline{p}\pi^+\pi^-$	$< 7.9 \times 10^{-4}$	CL=90%	1107
$\gamma\gamma$	$< 5 \times 10^{-4}$	CL=90%	1548
$\gamma\Lambda\overline{\Lambda}$	$< 1.3 \times 10^{-4}$	CL=90%	1074
3γ	$< 5.5 \times 10^{-5}$	CL=90%	1548
$\gamma f_J(2220)$	$> 2.50 \times 10^{-3}$	CL=99.9%	–
$\gamma f_0(1500)$	$(5.7 \pm 0.8) \times 10^{-4}$		1184
γe^+e^-	$(8.8 \pm 1.4) \times 10^{-3}$		–

$\chi_{c0}(1P)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 3417.3 \pm 2.8$ MeV
Full width $\Gamma = 14 \pm 5$ MeV

$\chi_{c0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(3.7 ± 0.7) %		1679
$\pi^+\pi^-K^+K^-$	(3.0 ± 0.7) %		1580
$\rho^0\pi^+\pi^-$	(1.6 ± 0.5) %		1608
$3(\pi^+\pi^-)$	(1.5 ± 0.5) %		1633
$K^+\overline{K}^*(892)^0\pi^- +$ c.c.	(1.2 ± 0.4) %		1522
$\pi^+\pi^-$	$(7.5 \pm 2.1) \times 10^{-3}$		1702
K^+K^-	$(7.1 \pm 2.4) \times 10^{-3}$		1635
$\pi^+\pi^-p\overline{p}$	$(5.0 \pm 2.0) \times 10^{-3}$		1320
$p\overline{p}$	$< 9.0 \times 10^{-4}$	90%	1427
Radiative decays			
$\gamma J/\psi(1S)$	$(6.6 \pm 1.8) \times 10^{-3}$		303
$\gamma\gamma$	$< 5 \times 10^{-4}$	95%	1708

$\chi_{c1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3510.53 \pm 0.12$ MeV
Full width $\Gamma = 0.88 \pm 0.14$ MeV

$\chi_{c1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
Hadronic decays		
$3(\pi^+\pi^-)$	(2.2 ± 0.8) %	1683
$2(\pi^+\pi^-)$	(1.6 ± 0.5) %	1727
$\pi^+\pi^-K^+K^-$	$(9 \pm 4) \times 10^{-3}$	1632
$\rho^0\pi^+\pi^-$	$(3.9 \pm 3.5) \times 10^{-3}$	1659
$K^+\overline{K}^*(892)^0\pi^- +$ c.c.	$(3.2 \pm 2.1) \times 10^{-3}$	1576
$\pi^+\pi^-p\overline{p}$	$(1.4 \pm 0.9) \times 10^{-3}$	1381
$p\overline{p}$	$(8.6 \pm 1.2) \times 10^{-5}$	1483
$\pi^+\pi^- + K^+K^-$	$< 2.1 \times 10^{-3}$	–
Radiative decays		
$\gamma J/\psi(1S)$	(27.3 ± 1.6) %	389

$\chi_{c2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 3556.17 \pm 0.13$ MeV
Full width $\Gamma = 2.00 \pm 0.18$ MeV

$\chi_{c2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(2.2 ± 0.5) %		1751
$\pi^+\pi^-K^+K^-$	(1.9 ± 0.5) %		1656
$3(\pi^+\pi^-)$	(1.2 ± 0.8) %		1707
$\rho^0\pi^+\pi^-$	$(7 \pm 4) \times 10^{-3}$		1683
$K^+\overline{K}^*(892)^0\pi^- +$ c.c.	$(4.8 \pm 2.8) \times 10^{-3}$		1601
$\pi^+\pi^-p\overline{p}$	$(3.3 \pm 1.3) \times 10^{-3}$		1410
$\pi^+\pi^-$	$(1.9 \pm 1.0) \times 10^{-3}$		1773
K^+K^-	$(1.5 \pm 1.1) \times 10^{-3}$		1708
$p\overline{p}$	$(10.0 \pm 1.0) \times 10^{-5}$		1510
$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%	185
Radiative decays			
$\gamma J/\psi(1S)$	(13.5 ± 1.1) %		430
$\gamma\gamma$	$(1.6 \pm 0.5) \times 10^{-4}$		1778

$\psi(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3686.00 \pm 0.09$ MeV
Full width $\Gamma = 277 \pm 31$ keV (S = 1.1)
$\Gamma_{ee} = 2.14 \pm 0.21$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$\psi(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons	(98.10 ± 0.30) %		–
virtual $\gamma \rightarrow$ hadrons	(2.9 ± 0.4) %		–
e^+e^-	$(8.5 \pm 0.7) \times 10^{-3}$		1843
$\mu^+\mu^-$	$(7.7 \pm 1.7) \times 10^{-3}$		1840
Decays into $J/\psi(1S)$ and anything			
$J/\psi(1S)$ anything	(54.2 ± 3.0) %		–
$J/\psi(1S)$ neutrals	(22.8 ± 1.7) %		–
$J/\psi(1S)\pi^+\pi^-$	(30.2 ± 1.9) %		477
$J/\psi(1S)\pi^0\pi^0$	(17.9 ± 1.8) %		481
$J/\psi(1S)\eta$	(2.7 ± 0.4) %	S=1.7	200
$J/\psi(1S)\pi^0$	$(9.7 \pm 2.1) \times 10^{-4}$		527
$J/\psi(1S)\mu^+\mu^-$	$(10.0 \pm 3.3) \times 10^{-3}$		–
Hadronic decays			
$3(\pi^+\pi^-)\pi^0$	$(3.5 \pm 1.6) \times 10^{-3}$		1746
$2(\pi^+\pi^-)\pi^0$	$(3.0 \pm 0.8) \times 10^{-3}$		1799
$\pi^+\pi^-K^+K^-$	$(1.6 \pm 0.4) \times 10^{-3}$		1726
$\pi^+\pi^-p\overline{p}$	$(8.0 \pm 2.0) \times 10^{-4}$		1491
$K^+\overline{K}^*(892)^0\pi^- +$ c.c.	$(6.7 \pm 2.5) \times 10^{-4}$		1673
$2(\pi^+\pi^-)$	$(4.5 \pm 1.0) \times 10^{-4}$		1817
$\rho^0\pi^+\pi^-$	$(4.2 \pm 1.5) \times 10^{-4}$		1751
$\overline{p}p$	$(1.9 \pm 0.5) \times 10^{-4}$		1586
$3(\pi^+\pi^-)$	$(1.5 \pm 1.0) \times 10^{-4}$		1774
$\overline{p}p\pi^0$	$(1.4 \pm 0.5) \times 10^{-4}$		1543
K^+K^-	$(1.0 \pm 0.7) \times 10^{-4}$		1776
$\pi^+\pi^-\pi^0$	$(9 \pm 5) \times 10^{-5}$		1830
$\rho\pi$	$< 8.3 \times 10^{-5}$	CL=90%	1760
$\pi^+\pi^-$	$(8 \pm 5) \times 10^{-5}$		1838
$\Lambda\overline{\Lambda}$	$< 4 \times 10^{-4}$	CL=90%	1467
$\Xi^-\overline{\Xi}^+$	$< 2 \times 10^{-4}$	CL=90%	1285
$K^+K^-\pi^0$	$< 2.96 \times 10^{-5}$	CL=90%	1754
$K^+\overline{K}^*(892)^- +$ c.c.	$< 5.4 \times 10^{-5}$	CL=90%	1698
Radiative decays			
$\gamma\chi_{c0}(1P)$	(9.3 ± 0.9) %		261
$\gamma\chi_{c1}(1P)$	(8.7 ± 0.8) %		171
$\gamma\chi_{c2}(1P)$	(7.8 ± 0.8) %		127
$\gamma\eta_c(1S)$	$(2.8 \pm 0.6) \times 10^{-3}$		639
$\gamma\eta'(958)$	$< 1.1 \times 10^{-3}$	CL=90%	1719
$\gamma\gamma$	$< 1.6 \times 10^{-4}$	CL=90%	1843
$\gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi$	$< 1.2 \times 10^{-4}$	CL=90%	1569

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 3769.9 \pm 2.5$ MeV (S = 1.8)
Full width $\Gamma = 23.6 \pm 2.7$ MeV (S = 1.1)
$\Gamma_{ee} = 0.26 \pm 0.04$ keV (S = 1.2)

$\psi(3770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$D\overline{D}$	dominant		242
e^+e^-	$(1.12 \pm 0.17) \times 10^{-5}$	1.2	1885

$\psi(4040)$ [lll]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4040 \pm 10$ MeV
Full width $\Gamma = 52 \pm 10$ MeV
$\Gamma_{ee} = 0.75 \pm 0.15$ keV

$\psi(4040)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(1.4 \pm 0.4) \times 10^{-5}$	2020
$D^0\overline{D}^0$	seen	777
$D^*(2007)^0\overline{D}^0 +$ c.c.	seen	578
$D^*(2007)^0\overline{D}^*(2007)^0$	seen	232

$\psi(4160)$ [iiii]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4159 \pm 20$ MeV
Full width $\Gamma = 78 \pm 20$ MeV
$\Gamma_{ee} = 0.77 \pm 0.23$ keV

$\psi(4160)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(10\pm4) \times 10^{-6}$	2079

$\psi(4415)$ [iiii]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4415 \pm 6$ MeV
Full width $\Gamma = 43 \pm 15$ MeV (S = 1.8)
$\Gamma_{ee} = 0.47 \pm 0.10$ keV

$\psi(4415)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
hadrons	dominant	–
e^+e^-	$(1.1\pm0.4) \times 10^{-5}$	2207

$b\overline{b}$ MESONS

$\Upsilon(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 9460.37 \pm 0.21$ MeV (S = 2.7)
Full width $\Gamma = 52.5 \pm 1.8$ keV
$\Gamma_{ee} = 1.32 \pm 0.05$ keV

$\Upsilon(1S)$ DECAY MODES	Fraction (Γ_i/Γ)		Scale factor/ Confidence level	p (MeV/c)
$\tau^+\tau^-$	$(2.67^{+0.14}_{-0.16})$ %			4384
e^+e^-	(2.52 ± 0.17) %			4730
$\mu^+\mu^-$	(2.48 ± 0.07) %		S=1.1	4729
	Hadronic decays			
$J/\psi(1S)$anything	$(1.1\ \pm0.4\ )$	$\times 10^{-3}$		4223
$\rho\pi$	< 2	$\times 10^{-4}$	CL=90%	4698
$\pi^+\pi^-$	< 5	$\times 10^{-4}$	CL=90%	4728
K^+K^-	< 5	$\times 10^{-4}$	CL=90%	4704
$p\overline{p}$	< 5	$\times 10^{-4}$	CL=90%	4636
	Radiative decays			
$\gamma 2h^+2h^-$	$(7.0\ \pm1.5\ )$	$\times 10^{-4}$		4720
$\gamma 3h^+3h^-$	$(5.4\ \pm2.0\ )$	$\times 10^{-4}$		4703
$\gamma 4h^+4h^-$	$(7.4\ \pm3.5\ )$	$\times 10^{-4}$		4679
$\gamma\pi^+\pi^-K^+K^-$	$(2.9\ \pm0.9\ )$	$\times 10^{-4}$		4686
$\gamma 2\pi^+2\pi^-$	$(2.5\ \pm0.9\ )$	$\times 10^{-4}$		4720
$\gamma 3\pi^+3\pi^-$	$(2.5\ \pm1.2\ )$	$\times 10^{-4}$		4703
$\gamma 2\pi^+2\pi^-K^+K^-$	$(2.4\ \pm1.2\ )$	$\times 10^{-4}$		4658
$\gamma\pi^+\pi^-p\overline{p}$	$(1.5\ \pm0.6\ )$	$\times 10^{-4}$		4604
$\gamma 2\pi^+2\pi^-p\overline{p}$	$(4\ \ \pm6\ \ )$	$\times 10^{-5}$		4563
$\gamma 2K^+2K^-$	$(2.0\ \pm2.0\ )$	$\times 10^{-5}$		4601
$\gamma\eta'(958)$	< 1.3	$\times 10^{-3}$	CL=90%	4682
$\gamma\eta$	< 3.5	$\times 10^{-4}$	CL=90%	4714
$\gamma f_2'(1525)$	< 1.4	$\times 10^{-4}$	CL=90%	4607
$\gamma f_2(1270)$	< 1.3	$\times 10^{-4}$	CL=90%	4644
$\gamma\eta(1440)$	< 8.2	$\times 10^{-5}$	CL=90%	4624
$\gamma f_J(1710) \to \gamma K\overline{K}$	< 2.6	$\times 10^{-4}$	CL=90%	4576
$\gamma f_0(2200) \to \gamma K^+K^-$	< 2	$\times 10^{-4}$	CL=90%	4475
$\gamma f_J(2220) \to \gamma K^+K^-$	< 1.5	$\times 10^{-5}$	CL=90%	4469
$\gamma\eta(2225) \to \gamma\phi\phi$	< 3	$\times 10^{-3}$	CL=90%	4469
γX	< 3	$\times 10^{-5}$	CL=90%	–
X = pseudoscalar with $m< 7.2$ GeV)				
$\gamma X\overline{X}$	< 1	$\times 10^{-3}$	CL=90%	–
$X\overline{X}$ = vectors with $m< 3.1$ GeV)				

$\chi_{b0}(1P)$ [jjjj]

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Mass $m = 9859.8 \pm 1.3$ MeV

$\chi_{b0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma\Upsilon(1S)$	<6 %	90%	391

$\chi_{b1}(1P)$ [jjjj]

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Mass $m = 9891.9 \pm 0.7$ MeV

$\chi_{b1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(1S)$	(35 ± 8) %	422

$\chi_{b2}(1P)$ [jjjj]

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Mass $m = 9913.2 \pm 0.6$ MeV

$\chi_{b2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(1S)$	(22 ± 4) %	443

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.02330 \pm 0.00031$ GeV
Full width $\Gamma = 44 \pm 7$ keV
$\Gamma_{ee} = 0.520 \pm 0.032$ keV

$\Upsilon(2S)$ DECAY MODES	Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$\Upsilon(1S)\pi^+\pi^-$	$(18.5\ \pm0.8\ )$ %			475
$\Upsilon(1S)\pi^0\pi^0$	$(\ 8.8\ \pm1.1\ )$ %			480
$\tau^+\tau^-$	$(\ 1.7\ \pm1.6\ )$ %			4686
$\mu^+\mu^-$	$(\ 1.31\pm0.21)$ %			5011
e^+e^-	$(\ 1.18\pm0.20)$ %			5012
$\Upsilon(1S)\pi^0$	< 8	$\times 10^{-3}$	90%	531
$\Upsilon(1S)\eta$	< 2	$\times 10^{-3}$	90%	127
$J/\psi(1S)$anything	< 6	$\times 10^{-3}$	90%	4533
	Radiative decays			
$\gamma\chi_{b1}(1P)$	$(\ 6.7\ \pm0.9\ )$ %			131
$\gamma\chi_{b2}(1P)$	$(\ 6.6\ \pm0.9\ )$ %			110
$\gamma\chi_{b0}(1P)$	$(\ 4.3\ \pm1.0\ )$ %			162
$\gamma f_J(1710)$	< 5.9	$\times 10^{-4}$	90%	4866
$\gamma f_2'(1525)$	< 5.3	$\times 10^{-4}$	90%	4896
$\gamma f_2(1270)$	< 2.41	$\times 10^{-4}$	90%	4931

$\chi_{b0}(2P)$ [jjjj]

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Mass $m = 10.2321 \pm 0.0006$ GeV

$\chi_{b0}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(2S)$	(4.6 ± 2.1) %	210
$\gamma\Upsilon(1S)$	$(9\ \ \pm6\ \ ) \times 10^{-3}$	746

$\chi_{b1}(2P)$ [jjjj]

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Mass $m = 10.2552 \pm 0.0005$ GeV
$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)} = 23.5 \pm 1.0$ MeV

$\chi_{b1}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\gamma\Upsilon(2S)$	$(21\ \ \pm4\ \ )$ %	1.5	229
$\gamma\Upsilon(1S)$	$(\ 8.5\pm1.3)$ %	1.3	764

$\chi_{b2}(2P)$ [jjjj]

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Mass $m = 10.2685 \pm 0.0004$ GeV
$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 13.5 \pm 0.6$ MeV

$\chi_{b2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(2S)$	(16.2 ± 2.4) %	242
$\gamma\Upsilon(1S)$	$(\ 7.1\pm1.0)$ %	776

$\Upsilon(3S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.3553 \pm 0.0005$ GeV
Full width $\Gamma = 26.3 \pm 3.5$ keV

$\Upsilon(3S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\Upsilon(2S)$anything	(10.6 ± 0.8) %		296
$\Upsilon(2S)\pi^+\pi^-$	(2.8 ± 0.6) %	S=2.2	177
$\Upsilon(2S)\pi^0\pi^0$	(2.00 ± 0.32) %		190
$\Upsilon(2S)\gamma\gamma$	(5.0 ± 0.7) %		327
$\Upsilon(1S)\pi^+\pi^-$	(4.48 ± 0.21) %		814
$\Upsilon(1S)\pi^0\pi^0$	(2.06 ± 0.28) %		816
$\Upsilon(1S)\eta$	$< 2.2 \times 10^{-3}$	CL=90%	–
$\mu^+\mu^-$	(1.81 ± 0.17) %		5177
e^+e^-	seen		5177
Radiative decays			
$\gamma\chi_{b2}(2P)$	(11.4 ± 0.8) %	S=1.3	87
$\gamma\chi_{b1}(2P)$	(11.3 ± 0.6) %		100
$\gamma\chi_{b0}(2P)$	(5.4 ± 0.6) %	S=1.1	123

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.5800 \pm 0.0035$ GeV
Full width $\Gamma = 10 \pm 4$ MeV
$\Gamma_{ee} = 0.248 \pm 0.031$ keV (S = 1.3)

$\Upsilon(4S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$B\overline{B}$	> 96 %	95%	–
non-$B\overline{B}$	< 4 %	95%	–
e^+e^-	$(2.8 \pm 0.7) \times 10^{-5}$		5290
$J/\psi(3097)$anything	$(2.2 \pm 0.7) \times 10^{-3}$		–
D^{*+}anything + c.c.	< 7.4 %	90%	5099
ϕanything	$< 2.3 \times 10^{-3}$	90%	5240
$\Upsilon(1S)$anything	$< 4 \times 10^{-3}$	90%	1053

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.865 \pm 0.008$ GeV (S = 1.1)
Full width $\Gamma = 110 \pm 13$ MeV
$\Gamma_{ee} = 0.31 \pm 0.07$ keV (S = 1.3)

$\Upsilon(10860)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(2.8 \pm 0.7) \times 10^{-6}$	5432

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 11.019 \pm 0.008$ GeV
Full width $\Gamma = 79 \pm 16$ MeV
$\Gamma_{ee} = 0.130 \pm 0.030$ keV

$\Upsilon(11020)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(1.6 \pm 0.5) \times 10^{-6}$	5509

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as S = $\sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] See the "Note on $\pi^\pm \to \ell^\pm \nu\gamma$ and $K^\pm \to \ell^\pm \nu\gamma$ Form Factors" in the $\pi^\pm$ Particle Listings for definitions and details.

[b] Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

[c] See the $\pi^\pm$ Particle Listings for the energy limits used in this measurement; low-energy γ's are not included.

[d] Derived from an analysis of neutrino-oscillation experiments.

[e] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the π^0 Particle Listings.

[f] See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

[g] C parity forbids this to occur as a single-photon process.

[h] See the "Note on scalar mesons" in the $f_0(1370)$ Particle Listings . The interpretation of this entry as a particle is controversial.

[i] See the "Note on $\rho(770)$" in the $\rho(770)$ Particle Listings .

[j] The e^+e^- branching fraction is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

[k] See the "Note on scalar mesons" in the $f_0(1370)$ Particle Listings .

[l] See the "Note on $a_1(1260)$" in the $a_1(1260)$ Particle Listings .

[m] This is only an educated guess; the error given is larger than the error on the average of the published values. See the Particle Listings for details.

[n] See the "Note on the $f_1(1420)$" in the $\eta(1440)$ Particle Listings.

[o] See also the $\omega(1600)$ Particle Listings.

[p] See the "Note on the $\eta(1440)$" in the $\eta(1440)$ Particle Listings.

[q] See the "Note on the $\rho(1450)$ and the $\rho(1700)$" in the $\rho(1700)$ Particle Listings.

[r] See the "Note on non-$q\overline{q}$ mesons" in the Particle Listings (see the index for the page number).

[s] See also the $\omega(1420)$ Particle Listings.

[t] See the "Note on $f_J(1710)$" in the $f_J(1710)$ Particle Listings .

[u] See the note in the $K^\pm$ Particle Listings.

[v] The definition of the slope parameter g of the $K \to 3\pi$ Dalitz plot is as follows (see also "Note on Dalitz Plot Parameters for $K \to 3\pi$ Decays" in the $K^\pm$ Particle Listings):

$$|M|^2 = 1 + g(s_3 - s_0)/m_{\pi^+}^2 + \cdots .$$

[w] For more details and definitions of parameters see the Particle Listings.

[x] See the $K^{\pm}$ Particle Listings for the energy limits used in this measurement.

[y] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[z] Direct-emission branching fraction.

[aa] Structure-dependent part.

[bb] Derived from measured values of ϕ_{+-}, ϕ_{00}, $|\eta|$, $|m_{K^0_L} - m_{K^0_S}|$, and $\tau_{K^0_S}$, as described in the introduction to "Tests of Conservation Laws."

[cc] The *CP*-violation parameters are defined as follows (see also "Note on *CP* Violation in $K_S \rightarrow 3\pi$" and "Note on *CP* Violation in K^0_L Decay" in the Particle Listings):

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = \frac{A(K^0_L \rightarrow \pi^+\pi^-)}{A(K^0_S \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}|e^{i\phi_{00}} = \frac{A(K^0_L \rightarrow \pi^0\pi^0)}{A(K^0_S \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

$$\delta = \frac{\Gamma(K^0_L \rightarrow \pi^-\ell^+\nu) - \Gamma(K^0_L \rightarrow \pi^+\ell^-\nu)}{\Gamma(K^0_L \rightarrow \pi^-\ell^+\nu) + \Gamma(K^0_L \rightarrow \pi^+\ell^-\nu)} ,$$

$$\text{Im}(\eta_{+-0})^2 = \frac{\Gamma(K^0_S \rightarrow \pi^+\pi^-\pi^0)^{CP \text{ viol.}}}{\Gamma(K^0_L \rightarrow \pi^+\pi^-\pi^0)} ,$$

$$\text{Im}(\eta_{000})^2 = \frac{\Gamma(K^0_S \rightarrow \pi^0\pi^0\pi^0)}{\Gamma(K^0_L \rightarrow \pi^0\pi^0\pi^0)} .$$

where for the last two relations *CPT* is assumed valid, *i.e.*, $\text{Re}(\eta_{+-0}) \simeq 0$ and $\text{Re}(\eta_{000}) \simeq 0$.

[dd] See the K^0_S Particle Listings for the energy limits used in this measurement.

[ee] Calculated from K^0_L semileptonic rates and the K^0_S lifetime assuming $\Delta S = \Delta Q$.

[ff] ϵ'/ϵ is derived from $|\eta_{00}/\eta_{+-}|$ measurements using theoretical input on phases.

[gg] The value is for the sum of the charge states of particle/antiparticle states indicated.

[hh] See the K^0_L Particle Listings for the energy limits used in this measurement.

[ii] Allowed by higher-order electroweak interactions.

[jj] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

[kk] See the "Note on $f_0(1370)$" in the $f_0(1370)$ Particle Listings and in the 1994 edition.

[ll] See the note in the $L(1770)$ Particle Listings in Reviews of Modern Physics **56** No. 2 Pt. II (1984), p. S200. See also the "Note on $K_2(1770)$ and the $K_2(1820)$" in the $K_2(1770)$ Particle Listings .

[mm] See the "Note on $K_2(1770)$ and the $K_2(1820)$" in the $K_2(1770)$ Particle Listings .

[nn] This is a weighted average of $D^{\pm}$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \rightarrow$ (η anything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in the Particle Listings.

[oo] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ here is really an e^+.

[pp] An ℓ indicates an e or a μ mode, not a sum over these modes.

[qq] The branching fraction for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers in the Particle Listings.

[rr] The two experiments measuring this fraction are in serious disagreement. See the Particle Listings.

[ss] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

[tt] The D^0_1-D^0_2 limits are inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via } \overline{D}^0))$ / $\Gamma(K^-\ell^+\nu_\ell)$.

[uu] The larger limit (from E791) allows interference between the doubly Cabibbo-suppressed and mixing amplitudes; the smaller limit (from E691) doesn't. See the papers for details.

[vv] The experiments on the division of this charge mode amongst its submodes disagree, and the submode branching fractions here add up to considerably more than the charged-mode fraction.

[ww] However, these upper limits are in serious disagreement with values obtained in another experiment.

[xx] For now, we average together measurements of the $X e^+\nu_e$ and $X\mu^+\nu_\mu$ branching fractions. This is the *average*, not the *sum*.

[yy] This branching fraction includes all the decay modes of the final-state resonance.

[zz] This value includes only K^+K^- decays of the $f_J(1710)$, because branching fractions of this resonance are not known.

[aaa] This value includes only $\pi^+\pi^-$ decays of the $f_0(1500)$, because branching fractions of this resonance are not known.

[bbb] B^0 and B^0_s contributions not separated. Limit is on weighted average of the two decay rates.

[ccc] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[ddd] D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances.

[eee] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

[fff] D_j represents an unresolved mixture of pseudoscalar and tensor D^{**} (*P*-wave) states.

[ggg] Not a pure measurement. See note at head of B^0_s Decay Modes.

[hhh] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[iii] J^{PC} known by production in e^+e^- via single photon annihilation. I^G is not known; interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

[jjj] Spectroscopic labeling for these states is theoretical, pending experimental information.

Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

- • Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.
- † Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED
($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	$X(1650)$	$0^+(?^{?-})$
• π^0	$1^-(0^{-+})$	• $\omega_3(1670)$	$0^-(3^{--})$
• η	$0^+(0^{-+})$	• $\pi_2(1670)$	$1^-(2^{-+})$
• $f_0(400\text{–}1200)$	$0^+(0^{++})$	• $\phi(1680)$	$0^-(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $\omega(782)$	$0^-(1^{--})$	• $\rho(1700)$	$1^+(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$	• $f_J(1710)$	$0^+(\text{even}^{++})$
• $f_0(980)$	$0^+(0^{++})$	$\eta(1760)$	$0^+(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$X(1775)$	$1^-(?^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	• $\pi(1800)$	$1^-(0^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	$f_2(1810)$	$0^+(2^{++})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $a_1(1260)$	$1^-(1^{++})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$X(1910)$	$0^+(?^{?+})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1950)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$X(2000)$	$1^-(?^{?+})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(2040)$	$1^-(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
$\hat{\rho}(1405)$	$1^-(1^{-+})$	$f_0(2060)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_0(2200)$	$0^+(0^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $\rho(1450)$	$1^+(1^{--})$		
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $\omega(1600)$	$0^-(1^{--})$	• $f_2(2340)$	$0^+(2^{++})$
$X(1600)$	$2^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
$\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
		$X(3250)$	$?^?(?^{??})$

OTHER LIGHT UNFLAVORED
($S = C = B = 0$)

$e^+e^-(1100\text{–}2200)$	$?^?(1^{--})$
$\overline{N}N(1100\text{–}3600)$	
$X(1900\text{–}3600)$	

STRANGE
($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED
($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^+$	$1/2(2^+)$

CHARMED, STRANGE
($C = S = \pm1$)

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{sJ}(2573)^\pm$	$0(?^?)$

BOTTOM
($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE
($B = \pm1$, $S = \mp1$)

	$I^G(J^{PC})$
• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED
($B = C = \pm1$)

$B^\pm_c$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$?^?(?^{?+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$?^?(1^{--})$
• $\psi(4040)$	$?^?(1^{--})$
• $\psi(4160)$	$?^?(1^{--})$
• $\psi(4415)$	$?^?(1^{--})$

$b\bar{b}$

• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$?^?(1^{--})$
• $\Upsilon(11020)$	$?^?(1^{--})$

NON-$q\bar{q}$ CANDIDATES

Non-$q\bar{q}$ Candidates

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. See our 1986 edition (Physics Letters **170B**) for listings of evidence for *Z* baryons (*KN* resonances).

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	**	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2370)$		**
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*			
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***			
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2593)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2625)^+$		***
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Sigma_c(2455)$		****
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Sigma_c(2520)$		***
									$\Sigma(2250)$		***	Ξ_c^+		***
									$\Sigma(2455)$		**	Ξ_c^0		***
									$\Sigma(2620)$		**	$\Xi_c(2645)$		***
									$\Sigma(3000)$		*	Ω_c^0		***
									$\Sigma(3170)$		*			
												Λ_b^0		***
												Ξ_b^0, Ξ_b^-		*

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

N BARYONS
$(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 938.27231 \pm 0.00028$ MeV [a]
$= 1.007276470 \pm 0.000000012$ u
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.0000000015 \pm 0.0000000011$
$|q_p + q_{\overline{p}}|/e < 2 \times 10^{-5}$
$|q_p + q_e|/e < 1.0 \times 10^{-21}$ [b]
Magnetic moment $\mu = 2.79284739 \pm 0.00000006\ \mu_N$
Electric dipole moment $d = (-4 \pm 6) \times 10^{-23}\ e\,\text{cm}$
Electric polarizability $\overline{\alpha} = (12.1 \pm 0.9) \times 10^{-4}\ \text{fm}^3$
Magnetic polarizability $\overline{\beta} = (2.1 \pm 0.9) \times 10^{-4}\ \text{fm}^3$
Mean life $\tau > 1.6 \times 10^{25}$ years (independent of mode)
$> 10^{31}$ to 5×10^{32} years [c] (mode dependent)

Below, for *N* decays, *p* and *n* distinguish proton and neutron partial lifetimes. See also the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1673) for a short review.

The "partial mean life" limits tabulated here are the limits on τ/B_j, where τ is the total mean life and B_j is the branching fraction for the mode in question.

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level	p (MeV/c)
Antilepton + meson			
$N \to e^+\pi$	> 130 (n), > 550 (p)	90%	459
$N \to \mu^+\pi$	> 100 (n), > 270 (p)	90%	453
$N \to \nu\pi$	> 100 (n), > 25 (p)	90%	459
$p \to e^+\eta$	> 140	90%	309
$p \to \mu^+\eta$	> 69	90%	296
$n \to \nu\eta$	> 54	90%	310
$N \to e^+\rho$	> 58 (n), > 75 (p)	90%	153
$N \to \mu^+\rho$	> 23 (n), > 110 (p)	90%	119
$N \to \nu\rho$	> 19 (n), > 27 (p)	90%	153
$p \to e^+\omega$	> 45	90%	142
$p \to \mu^+\omega$	> 57	90%	104
$n \to \nu\omega$	> 43	90%	144
$N \to e^+K$	> 1.3 (n), > 150 (p)	90%	337
$p \to e^+K^0_S$	> 76	90%	337
$p \to e^+K^0_L$	> 44	90%	337
$N \to \mu^+K$	> 1.1 (n), > 120 (p)	90%	326
$p \to \mu^+K^0_S$	> 64	90%	326
$p \to \mu^+K^0_L$	> 44	90%	326
$N \to \nu K$	> 86 (n), > 100 (p)	90%	339
$p \to e^+K^*(892)^0$	> 52	90%	45
$N \to \nu K^*(892)$	> 22 (n), > 20 (p)	90%	45
Antilepton + mesons			
$p \to e^+\pi^+\pi^-$	> 21	90%	448
$p \to e^+\pi^0\pi^0$	> 38	90%	449
$n \to e^+\pi^-\pi^0$	> 32	90%	449
$p \to \mu^+\pi^+\pi^-$	> 17	90%	425
$p \to \mu^+\pi^0\pi^0$	> 33	90%	427
$n \to \mu^+\pi^-\pi^0$	> 33	90%	427
$n \to e^+K^0\pi^-$	> 18	90%	319
Lepton + meson			
$n \to e^-\pi^+$	> 65	90%	459
$n \to \mu^-\pi^+$	> 49	90%	453
$n \to e^-\rho^+$	> 62	90%	154
$n \to \mu^-\rho^+$	> 7	90%	120
$n \to e^-K^+$	> 32	90%	340
$n \to \mu^-K^+$	> 57	90%	330
Lepton + mesons			
$p \to e^-\pi^+\pi^+$	> 30	90%	448
$n \to e^-\pi^+\pi^0$	> 29	90%	449
$p \to \mu^-\pi^+\pi^+$	> 17	90%	425
$n \to \mu^-\pi^+\pi^0$	> 34	90%	427
$p \to e^-\pi^+K^+$	> 20	90%	320
$p \to \mu^-\pi^+K^+$	> 5	90%	279
Antilepton + photon(s)			
$p \to e^+\gamma$	> 460	90%	469
$p \to \mu^+\gamma$	> 380	90%	463
$n \to \nu\gamma$	> 24	90%	470
$p \to e^+\gamma\gamma$	> 100	90%	469
Three (or more) leptons			
$p \to e^+e^+e^-$	> 510	90%	469
$p \to e^+\mu^+\mu^-$	> 81	90%	457
$p \to e^+\nu\nu$	> 11	90%	469
$n \to e^+e^-\nu$	> 74	90%	470
$n \to \mu^+e^-\nu$	> 47	90%	464
$n \to \mu^+\mu^-\nu$	> 42	90%	458
$p \to \mu^+e^+e^-$	> 91	90%	464
$p \to \mu^+\mu^+\mu^-$	> 190	90%	439
$p \to \mu^+\nu\nu$	> 21	90%	463
$p \to e^-\mu^+\mu^+$	> 6	90%	457
$n \to 3\nu$	> 0.0005	90%	470
Inclusive modes			
$N \to e^+$anything	> 0.6 (n, p)	90%	–
$N \to \mu^+$anything	> 12 (n, p)	90%	–
$N \to e^+\pi^0$anything	> 0.6 (n, p)	90%	–
$\Delta B = 2$ dinucleon modes			
The following are lifetime limits per iron nucleus.			
$pp \to \pi^+\pi^+$	> 0.7	90%	–
$pn \to \pi^+\pi^0$	> 2	90%	–
$nn \to \pi^+\pi^-$	> 0.7	90%	–
$nn \to \pi^0\pi^0$	> 3.4	90%	–
$pp \to e^+e^+$	> 5.8	90%	–
$pp \to e^+\mu^+$	> 3.6	90%	–
$pp \to \mu^+\mu^+$	> 1.7	90%	–
$pn \to e^+\overline{\nu}$	> 2.8	90%	–
$pn \to \mu^+\overline{\nu}$	> 1.6	90%	–
$nn \to \nu_e\overline{\nu}_e$	> 0.000012	90%	–
$nn \to \nu_\mu\overline{\nu}_\mu$	> 0.000006	90%	–

$\overline{p}$ DECAY MODES

$\overline{p}$ DECAY MODES	Partial mean life (years)	Confidence level	p (MeV/c)
$\overline{p} \to e^-\gamma$	> 1848	95%	469
$\overline{p} \to e^-\pi^0$	> 554	95%	459
$\overline{p} \to e^-\eta$	> 171	95%	309
$\overline{p} \to e^-K^0_S$	> 29	95%	337
$\overline{p} \to e^-K^0_L$	> 9	95%	337

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 939.56563 \pm 0.00028$ MeV [a]
$= 1.008664904 \pm 0.000000014$ u
$m_n - m_p = 1.293318 \pm 0.000009$ MeV
$= 0.001388434 \pm 0.000000009$ u
Mean life $\tau = 886.7 \pm 1.9$ s (S = 1.2)
$c\tau = 2.658 \times 10^8$ km
Magnetic moment $\mu = -1.9130428 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.97 \times 10^{-25}\ e\,\text{cm}$, CL = 90%
Electric polarizability $\alpha = (0.98^{+0.19}_{-0.23}) \times 10^{-3}\ \text{fm}^3$ (S = 1.1)
Charge $q = (-0.4 \pm 1.1) \times 10^{-21}\ e$
Mean $n\overline{n}$-oscillation time $> 1.2 \times 10^8$ s, CL = 90% [d] (bound n)
$> 0.86 \times 10^8$ s, CL = 90% (free n)

Decay parameters [e]

$pe^-\overline{\nu}_e$	$g_A/g_V = -1.2670 \pm 0.0035$ (S = 1.9)
"	$A = -0.1162 \pm 0.0013$ (S = 1.8)
"	$B = 0.990 \pm 0.008$
"	$a = -0.102 \pm 0.005$
"	$\phi_{AV} = (180.07 \pm 0.18)^\circ$ [f]
"	$D = (-0.5 \pm 1.4) \times 10^{-3}$

n DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$pe^-\overline{\nu}_e$	100 %		1.19
Charge conservation (Q) violating mode			
$p\nu_e\overline{\nu}_e$	$Q < 8 \times 10^{-27}$	68%	1.29

$N(1440)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Breit-Wigner mass = 1430 to 1470 (≈ 1440) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV
$p_{\text{beam}} = 0.61$ GeV/c $4\pi\bar{\lambda}^2 = 31.0$ mb
Re(pole position) = 1345 to 1385 (≈ 1365) MeV
−2Im(pole position) = 160 to 260 (≈ 210) MeV

$N(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	397
$N\pi\pi$	30–40 %	342
$\Delta\pi$	20–30 %	143
$N\rho$	<8 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–10 %	–
$p\gamma$	0.035–0.048 %	414
$p\gamma$, helicity=1/2	0.035–0.048 %	414
$n\gamma$	0.009–0.032 %	413
$n\gamma$, helicity=1/2	0.009–0.032 %	413

$N(1520)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Breit-Wigner mass = 1515 to 1530 (≈ 1520) MeV
Breit-Wigner full width = 110 to 135 (≈ 120) MeV
$p_{\text{beam}} = 0.74$ GeV/c $4\pi\bar{\lambda}^2 = 23.5$ mb
Re(pole position) = 1505 to 1515 (≈ 1510) MeV
−2Im(pole position) = 110 to 120 (≈ 115) MeV

$N(1520)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	50–60 %	456
$N\pi\pi$	40–50 %	410
$\Delta\pi$	15–25 %	228
$N\rho$	15–25 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %	–
$p\gamma$	0.46–0.56 %	470
$p\gamma$, helicity=1/2	0.001–0.034 %	470
$p\gamma$, helicity=3/2	0.44–0.53 %	470
$n\gamma$	0.30–0.53 %	470
$n\gamma$, helicity=1/2	0.04–0.10 %	470
$n\gamma$, helicity=3/2	0.25–0.45 %	470

$N(1535)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Breit-Wigner mass = 1520 to 1555 (≈ 1535) MeV
Breit-Wigner full width = 100 to 250 (≈ 150) MeV
$p_{\text{beam}} = 0.76$ GeV/c $4\pi\bar{\lambda}^2 = 22.5$ mb
Re(pole position) = 1495 to 1515 (≈ 1505) MeV
−2Im(pole position) = 90 to 250 (≈ 170) MeV

$N(1535)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–55 %	467
$N\eta$	30–55 %	182
$N\pi\pi$	1–10 %	422
$\Delta\pi$	<1 %	242
$N\rho$	<4 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<3 %	–
$N(1440)\pi$	<7 %	†
$p\gamma$	0.15–0.35 %	481
$p\gamma$, helicity=1/2	0.15–0.35 %	481
$n\gamma$	0.004–0.29 %	480
$n\gamma$, helicity=1/2	0.004–0.29 %	480

$N(1650)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Breit-Wigner mass = 1640 to 1680 (≈ 1650) MeV
Breit-Wigner full width = 145 to 190 (≈ 150) MeV
$p_{\text{beam}} = 0.96$ GeV/c $4\pi\bar{\lambda}^2 = 16.4$ mb
Re(pole position) = 1640 to 1680 (≈ 1660) MeV
−2Im(pole position) = 150 to 170 (≈ 160) MeV

$N(1650)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–90 %	547
$N\eta$	3–10 %	346
ΛK	3–11 %	161
$N\pi\pi$	10–20 %	511
$\Delta\pi$	1–7 %	344
$N\rho$	4–12 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<4 %	–
$N(1440)\pi$	<5 %	147
$p\gamma$	0.04–0.18 %	558
$p\gamma$, helicity=1/2	0.04–0.18 %	558
$n\gamma$	0.003–0.17 %	557
$n\gamma$, helicity=1/2	0.003–0.17 %	557

$N(1675)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$

Breit-Wigner mass = 1670 to 1685 (≈ 1675) MeV
Breit-Wigner full width = 140 to 180 (≈ 150) MeV
$p_{\text{beam}} = 1.01$ GeV/c $4\pi\bar{\lambda}^2 = 15.4$ mb
Re(pole position) = 1655 to 1665 (≈ 1660) MeV
−2Im(pole position) = 125 to 155 (≈ 140) MeV

$N(1675)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	40–50 %	563
ΛK	<1 %	209
$N\pi\pi$	50–60 %	529
$\Delta\pi$	50–60 %	364
$N\rho$	< 1–3 %	†
$p\gamma$	0.004–0.023 %	575
$p\gamma$, helicity=1/2	0.0–0.015 %	575
$p\gamma$, helicity=3/2	0.0–0.011 %	575
$n\gamma$	0.02–0.12 %	574
$n\gamma$, helicity=1/2	0.006–0.046 %	574
$n\gamma$, helicity=3/2	0.01–0.08 %	574

$N(1680)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$

Breit-Wigner mass = 1675 to 1690 (≈ 1680) MeV
Breit-Wigner full width = 120 to 140 (≈ 130) MeV
$p_{\text{beam}} = 1.01$ GeV/c $4\pi\bar{\lambda}^2 = 15.2$ mb
Re(pole position) = 1665 to 1675 (≈ 1670) MeV
−2Im(pole position) = 105 to 135 (≈ 120) MeV

$N(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	567
$N\pi\pi$	30–40 %	532
$\Delta\pi$	5–15 %	369
$N\rho$	3–15 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %	–
$p\gamma$	0.21–0.32 %	578
$p\gamma$, helicity=1/2	0.001–0.011 %	578
$p\gamma$, helicity=3/2	0.20–0.32 %	578
$n\gamma$	0.021–0.046 %	577
$n\gamma$, helicity=1/2	0.004–0.029 %	577
$n\gamma$, helicity=3/2	0.01–0.024 %	577

$N(1700)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Breit-Wigner mass = 1650 to 1750 (≈ 1700) MeV
Breit-Wigner full width = 50 to 150 (≈ 100) MeV
$p_{\text{beam}} = 1.05$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 14.5$ mb
Re(pole position) = 1630 to 1730 (≈ 1680) MeV
−2Im(pole position) = 50 to 150 (≈ 100) MeV

$N(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	580
ΛK	<3 %	250
$N\pi\pi$	85–95 %	547
$N\rho$	<35 %	†
$p\gamma$	0.01–0.05 %	591
$p\gamma$, helicity=1/2	0.0–0.024 %	591
$p\gamma$, helicity=3/2	0.002–0.026 %	591
$n\gamma$	0.01–0.13 %	590
$n\gamma$, helicity=1/2	0.0–0.09 %	590
$n\gamma$, helicity=3/2	0.01–0.05 %	590

$N(1710)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Breit-Wigner mass = 1680 to 1740 (≈ 1710) MeV
Breit-Wigner full width = 50 to 250 (≈ 100) MeV
$p_{\text{beam}} = 1.07$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 14.2$ mb
Re(pole position) = 1670 to 1770 (≈ 1720) MeV
−2Im(pole position) = 80 to 380 (≈ 230) MeV

$N(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	587
ΛK	5–25 %	264
$N\pi\pi$	40–90 %	554
$\Delta\pi$	15–40 %	393
$N\rho$	5–25 %	48
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %	–
$p\gamma$	0.002–0.05%	598
$p\gamma$, helicity=1/2	0.002–0.05%	598
$n\gamma$	0.0–0.02%	597
$n\gamma$, helicity=1/2	0.0–0.02%	597

$N(1720)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

Breit-Wigner mass = 1650 to 1750 (≈ 1720) MeV
Breit-Wigner full width = 100 to 200 (≈ 150) MeV
$p_{\text{beam}} = 1.09$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 13.9$ mb
Re(pole position) = 1650 to 1750 (≈ 1700) MeV
−2Im(pole position) = 110 to 390 (≈ 250) MeV

$N(1720)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	594
ΛK	1–15 %	278
$N\pi\pi$	>70 %	561
$N\rho$	70–85 %	104
$p\gamma$	0.003–0.10 %	604
$p\gamma$, helicity=1/2	0.003–0.08 %	604
$p\gamma$, helicity=3/2	0.001–0.03 %	604
$n\gamma$	0.002–0.39 %	603
$n\gamma$, helicity=1/2	0.0–0.002 %	603
$n\gamma$, helicity=3/2	0.001–0.39 %	603

$N(2190)\ G_{17}$

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$

Breit-Wigner mass = 2100 to 2200 (≈ 2190) MeV
Breit-Wigner full width = 350 to 550 (≈ 450) MeV
$p_{\text{beam}} = 2.07$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 6.21$ mb
Re(pole position) = 1950 to 2150 (≈ 2050) MeV
−2Im(pole position) = 350 to 550 (≈ 450) MeV

$N(2190)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	888

$N(2220)\ H_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$

Breit-Wigner mass = 2180 to 2310 (≈ 2220) MeV
Breit-Wigner full width = 320 to 550 (≈ 400) MeV
$p_{\text{beam}} = 2.14$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 5.97$ mb
Re(pole position) = 2100 to 2240 (≈ 2170) MeV
−2Im(pole position) = 370 to 570 (≈ 470) MeV

$N(2220)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	905

$N(2250)\ G_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$

Breit-Wigner mass = 2170 to 2310 (≈ 2250) MeV
Breit-Wigner full width = 290 to 470 (≈ 400) MeV
$p_{\text{beam}} = 2.21$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 5.74$ mb
Re(pole position) = 2080 to 2200 (≈ 2140) MeV
−2Im(pole position) = 280 to 680 (≈ 480) MeV

$N(2250)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	923

$N(2600)\ I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$

Breit-Wigner mass = 2550 to 2750 (≈ 2600) MeV
Breit-Wigner full width = 500 to 800 (≈ 650) MeV
$p_{\text{beam}} = 3.12$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 3.86$ mb

$N(2600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–10 %	1126

Δ BARYONS
$(S = 0,\ I = 3/2)$

$\Delta^{++} = uuu,\quad \Delta^{+} = uud,\quad \Delta^{0} = udd,\quad \Delta^{-} = ddd$

$\Delta(1232)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Breit-Wigner mass (mixed charges) = 1230 to 1234 (≈ 1232) MeV
Breit-Wigner full width (mixed charges) = 115 to 125 (≈ 120) MeV
$p_{\text{beam}} = 0.30$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 94.8$ mb
Re(pole position) = 1209 to 1211 (≈ 1210) MeV
−2Im(pole position) = 98 to 102 (≈ 100) MeV

$\Delta(1232)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	>99 %	227
$N\gamma$	0.52–0.60 %	259
$N\gamma$, helicity=1/2	0.11–0.13 %	259
$N\gamma$, helicity=3/2	0.41–0.47 %	259

$\Delta(1600)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Breit-Wigner mass = 1550 to 1700 (≈ 1600) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV
$p_{\text{beam}} = 0.87$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 18.6$ mb
Re(pole position) = 1500 to 1700 (≈ 1600) MeV
−2Im(pole position) = 200 to 400 (≈ 300) MeV

$\Delta(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–25 %	512
$N\pi\pi$	75–90 %	473
$\Delta\pi$	40–70 %	301
$N\rho$	<25 %	†
$N(1440)\pi$	10–35 %	74
$N\gamma$	0.001–0.02 %	525
$N\gamma$, helicity=1/2	0.0–0.02 %	525
$N\gamma$, helicity=3/2	0.001–0.005 %	525

$\Delta(1620)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$

Breit-Wigner mass = 1615 to 1675 (≈ 1620) MeV
Breit-Wigner full width = 120 to 180 (≈ 150) MeV
$p_{\mathrm{beam}} = 0.91$ GeV/c $4\pi\lambda\!\!\!^{-2} = 17.7$ mb
Re(pole position) = 1580 to 1620 (≈ 1600) MeV
−2Im(pole position) = 100 to 130 (≈ 115) MeV

Δ(1620) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	20–30 %	526
$N\pi\pi$	70–80 %	488
$\Delta\pi$	30–60 %	318
$N\rho$	7–25 %	†
$N\gamma$	0.004–0.044 %	538
$N\gamma$, helicity=1/2	0.004–0.044 %	538

$\Delta(1700)\ D_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$

Breit-Wigner mass = 1670 to 1770 (≈ 1700) MeV
Breit-Wigner full width = 200 to 400 (≈ 300) MeV
$p_{\mathrm{beam}} = 1.05$ GeV/c $4\pi\lambda\!\!\!^{-2} = 14.5$ mb
Re(pole position) = 1620 to 1700 (≈ 1660) MeV
−2Im(pole position) = 150 to 250 (≈ 200) MeV

Δ(1700) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	580
$N\pi\pi$	80–90 %	547
$\Delta\pi$	30–60 %	385
$N\rho$	30–55 %	†
$N\gamma$	0.12–0.26 %	591
$N\gamma$, helicity=1/2	0.08–0.16 %	591
$N\gamma$, helicity=3/2	0.025–0.12 %	591

$\Delta(1905)\ F_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$

Breit-Wigner mass = 1870 to 1920 (≈ 1905) MeV
Breit-Wigner full width = 280 to 440 (≈ 350) MeV
$p_{\mathrm{beam}} = 1.45$ GeV/c $4\pi\lambda\!\!\!^{-2} = 9.62$ mb
Re(pole position) = 1800 to 1860 (≈ 1830) MeV
−2Im(pole position) = 230 to 330 (≈ 280) MeV

Δ(1905) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	713
$N\pi\pi$	85–95 %	687
$\Delta\pi$	<25 %	542
$N\rho$	>60 %	421
$N\gamma$	0.01–0.03 %	721
$N\gamma$, helicity=1/2	0.0–0.1 %	721
$N\gamma$, helicity=3/2	0.004–0.03 %	721

$\Delta(1910)\ P_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$

Breit-Wigner mass = 1870 to 1920 (≈ 1910) MeV
Breit-Wigner full width = 190 to 270 (≈ 250) MeV
$p_{\mathrm{beam}} = 1.46$ GeV/c $4\pi\lambda\!\!\!^{-2} = 9.54$ mb
Re(pole position) = 1830 to 1880 (≈ 1855) MeV
−2Im(pole position) = 200 to 500 (≈ 350) MeV

Δ(1910) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	15–30 %	716
$N\gamma$	0.0–0.2 %	725
$N\gamma$, helicity=1/2	0.0–0.2 %	725

$\Delta(1920)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Breit-Wigner mass = 1900 to 1970 (≈ 1920) MeV
Breit-Wigner full width = 150 to 300 (≈ 200) MeV
$p_{\mathrm{beam}} = 1.48$ GeV/c $4\pi\lambda\!\!\!^{-2} = 9.37$ mb
Re(pole position) = 1850 to 1950 (≈ 1900) MeV
−2Im(pole position) = 200 to 400 (≈ 300) MeV

Δ(1920) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–20 %	722

$\Delta(1930)\ D_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$

Breit-Wigner mass = 1920 to 1970 (≈ 1930) MeV
Breit-Wigner full width = 250 to 450 (≈ 350) MeV
$p_{\mathrm{beam}} = 1.50$ GeV/c $4\pi\lambda\!\!\!^{-2} = 9.21$ mb
Re(pole position) = 1840 to 1940 (≈ 1890) MeV
−2Im(pole position) = 200 to 300 (≈ 250) MeV

Δ(1930) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	729
$N\gamma$	0.0–0.02 %	737
$N\gamma$, helicity=1/2	0.0–0.01 %	737
$N\gamma$, helicity=3/2	0.0–0.01 %	737

$\Delta(1950)\ F_{37}$

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$

Breit-Wigner mass = 1940 to 1960 (≈ 1950) MeV
Breit-Wigner full width = 290 to 350 (≈ 300) MeV
$p_{\mathrm{beam}} = 1.54$ GeV/c $4\pi\lambda\!\!\!^{-2} = 8.91$ mb
Re(pole position) = 1880 to 1890 (≈ 1885) MeV
−2Im(pole position) = 210 to 270 (≈ 240) MeV

Δ(1950) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–40 %	741
$N\pi\pi$		716
$\Delta\pi$	20–30 %	574
$N\rho$	<10 %	469
$N\gamma$	0.08–0.13 %	749
$N\gamma$, helicity=1/2	0.03–0.055 %	749
$N\gamma$, helicity=3/2	0.05–0.075 %	749

$\Delta(2420)\ H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$

Breit-Wigner mass = 2300 to 2500 (≈ 2420) MeV
Breit-Wigner full width = 300 to 500 (≈ 400) MeV
$p_{\mathrm{beam}} = 2.64$ GeV/c $4\pi\lambda\!\!\!^{-2} = 4.68$ mb
Re(pole position) = 2260 to 2400 (≈ 2330) MeV
−2Im(pole position) = 350 to 750 (≈ 550) MeV

Δ(2420) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	1023

Λ BARYONS
$(S = -1, I = 0)$

$\Lambda^0 = uds$

Λ

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1115.683 \pm 0.006$ MeV
Mean life $\tau = (2.632 \pm 0.020) \times 10^{-10}$ s (S = 1.6)
$c\tau = 7.89$ cm
Magnetic moment $\mu = -0.613 \pm 0.004\ \mu_N$
Electric dipole moment $d < 1.5 \times 10^{-16}$ $e$cm, CL = 95%

Decay parameters

$p\pi^-$ $\alpha_- = 0.642 \pm 0.013$
" $\phi_- = (-6.5 \pm 3.5)^\circ$
" $\gamma_- = 0.76$ [g]
" $\Delta_- = (8 \pm 4)^\circ$ [g]
$n\pi^0$ $\alpha_0 = +0.65 \pm 0.05$
$pe^-\overline{\nu}_e$ $g_A/g_V = -0.718 \pm 0.015$ [e]

Λ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$p\pi^-$	(63.9 ± 0.5) %	101
$n\pi^0$	(35.8 ± 0.5) %	104
$n\gamma$	$(1.75 \pm 0.15) \times 10^{-3}$	162
$p\pi^-\gamma$	[h] $(8.4 \pm 1.4) \times 10^{-4}$	101
$pe^-\overline{\nu}_e$	$(8.32 \pm 0.14) \times 10^{-4}$	163
$p\mu^-\overline{\nu}_\mu$	$(1.57 \pm 0.35) \times 10^{-4}$	131

$\Lambda(1405)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1407 \pm 4$ MeV
Full width $\Gamma = 50.0 \pm 2.0$ MeV
Below $\overline{K}N$ threshold

$\Lambda(1405)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

$\Lambda(1520)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass $m = 1519.5 \pm 1.0$ MeV [i]
Full width $\Gamma = 15.6 \pm 1.0$ MeV [i]
$p_{\text{beam}} = 0.39$ GeV/c $4\pi\lambda\!\!\!^{-2} = 82.8$ mb

$\Lambda(1520)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	45 ± 1%	244
$\Sigma\pi$	42 ± 1%	267
$\Lambda\pi\pi$	10 ± 1%	252
$\Sigma\pi\pi$	0.9 ± 0.1%	152
$\Lambda\gamma$	0.8 ± 0.2%	351

$\Lambda(1600)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1560$ to 1700 (≈ 1600) MeV
Full width $\Gamma = 50$ to 250 (≈ 150) MeV
$p_{\text{beam}} = 0.58$ GeV/c $4\pi\lambda\!\!\!^{-2} = 41.6$ mb

$\Lambda(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	15–30 %	343
$\Sigma\pi$	10–60 %	336

$\Lambda(1670)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1660$ to 1680 (≈ 1670) MeV
Full width $\Gamma = 25$ to 50 (≈ 35) MeV
$p_{\text{beam}} = 0.74$ GeV/c $4\pi\lambda\!\!\!^{-2} = 28.5$ mb

$\Lambda(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	15–25 %	414
$\Sigma\pi$	20–60 %	393
$\Lambda\eta$	15–35 %	64

$\Lambda(1690)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass $m = 1685$ to 1695 (≈ 1690) MeV
Full width $\Gamma = 50$ to 70 (≈ 60) MeV
$p_{\text{beam}} = 0.78$ GeV/c $4\pi\lambda\!\!\!^{-2} = 26.1$ mb

$\Lambda(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–30 %	433
$\Sigma\pi$	20–40 %	409
$\Lambda\pi\pi$	$\sim$ 25 %	415
$\Sigma\pi\pi$	$\sim$ 20 %	350

$\Lambda(1800)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1720$ to 1850 (≈ 1800) MeV
Full width $\Gamma = 200$ to 400 (≈ 300) MeV
$p_{\text{beam}} = 1.01$ GeV/c $4\pi\lambda\!\!\!^{-2} = 17.5$ mb

$\Lambda(1800)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–40 %	528
$\Sigma\pi$	seen	493
$\Sigma(1385)\pi$	seen	345
$N\overline{K}^*(892)$	seen	†

$\Lambda(1810)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1750$ to 1850 (≈ 1810) MeV
Full width $\Gamma = 50$ to 250 (≈ 150) MeV
$p_{\text{beam}} = 1.04$ GeV/c $4\pi\lambda\!\!\!^{-2} = 17.0$ mb

$\Lambda(1810)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–50 %	537
$\Sigma\pi$	10–40 %	501
$\Sigma(1385)\pi$	seen	356
$N\overline{K}^*(892)$	30–60 %	†

$\Lambda(1820)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass $m = 1815$ to 1825 (≈ 1820) MeV
Full width $\Gamma = 70$ to 90 (≈ 80) MeV
$p_{\text{beam}} = 1.06$ GeV/c $4\pi\lambda\!\!\!^{-2} = 16.5$ mb

$\Lambda(1820)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	55–65 %	545
$\Sigma\pi$	8–14 %	508
$\Sigma(1385)\pi$	5–10 %	362

$\Lambda(1830)\ D_{05}$

$I(J^P) = 0(\frac{5}{2}^-)$

Mass $m = 1810$ to 1830 (≈ 1830) MeV
Full width $\Gamma = 60$ to 110 (≈ 95) MeV
$p_{\text{beam}} = 1.08$ GeV/c $4\pi\lambda\!\!\!^{-2} = 16.0$ mb

$\Lambda(1830)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	3–10 %	553
$\Sigma\pi$	35–75 %	515
$\Sigma(1385)\pi$	>15 %	371

$\Lambda(1890)\ P_{03}$

$I(J^P) = 0(\frac{3}{2}^+)$

Mass $m = 1850$ to 1910 (≈ 1890) MeV
Full width $\Gamma = 60$ to 200 (≈ 100) MeV
$p_{\rm beam} = 1.21$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 13.6$ mb

$\Lambda(1890)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–35 %	599
$\Sigma\pi$	3–10 %	559
$\Sigma(1385)\pi$	seen	420
$N\overline{K}^*(892)$	seen	233

$\Lambda(2100)\ G_{07}$

$I(J^P) = 0(\frac{7}{2}^-)$

Mass $m = 2090$ to 2110 (≈ 2100) MeV
Full width $\Gamma = 100$ to 250 (≈ 200) MeV
$p_{\rm beam} = 1.68$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 8.68$ mb

$\Lambda(2100)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–35 %	751
$\Sigma\pi$	~ 5 %	704
$\Lambda\eta$	<3 %	617
ΞK	<3 %	483
$\Lambda\omega$	<8 %	443
$N\overline{K}^*(892)$	10–20 %	514

$\Lambda(2110)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass $m = 2090$ to 2140 (≈ 2110) MeV
Full width $\Gamma = 150$ to 250 (≈ 200) MeV
$p_{\rm beam} = 1.70$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 8.53$ mb

$\Lambda(2110)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–25 %	757
$\Sigma\pi$	10–40 %	711
$\Lambda\omega$	seen	455
$\Sigma(1385)\pi$	seen	589
$N\overline{K}^*(892)$	10–60 %	524

$\Lambda(2350)\ H_{09}$

$I(J^P) = 0(\frac{9}{2}^+)$

Mass $m = 2340$ to 2370 (≈ 2350) MeV
Full width $\Gamma = 100$ to 250 (≈ 150) MeV
$p_{\rm beam} = 2.29$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 5.85$ mb

$\Lambda(2350)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	~ 12 %	915
$\Sigma\pi$	~ 10 %	867

Σ BARYONS
($S = -1$, $I = 1$)

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1189.37 \pm 0.07$ MeV (S = 2.2)
Mean life $\tau = (0.799 \pm 0.004) \times 10^{-10}$ s
$c\tau = 2.396$ cm
Magnetic moment $\mu = 2.458 \pm 0.010\ \mu_N$ (S = 2.1)
$\Gamma(\Sigma^+ \rightarrow n\ell^+\nu)/\Gamma(\Sigma^- \rightarrow n\ell^-\overline{\nu}) < 0.043$

Decay parameters

$p\pi^0$	$\alpha_0 = -0.980^{+0.017}_{-0.015}$
"	$\phi_0 = (36 \pm 34)^\circ$
"	$\gamma_0 = 0.16$ [g]
"	$\Delta_0 = (187 \pm 6)^\circ$ [g]
$n\pi^+$	$\alpha_+ = 0.068 \pm 0.013$
"	$\phi_+ = (167 \pm 20)^\circ$ (S = 1.1)
"	$\gamma_+ = -0.97$ [g]
"	$\Delta_+ = (-73^{+133}_{-10})^\circ$ [g]
$p\gamma$	$\alpha_\gamma = -0.76 \pm 0.08$

Σ^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p\pi^0$		(51.57 ± 0.30) %		189
$n\pi^+$		(48.31 ± 0.30) %		185
$p\gamma$		$(1.23 \pm 0.05) \times 10^{-3}$		225
$n\pi^+\gamma$	[h]	$(4.5 \pm 0.5) \times 10^{-4}$		185
$\Lambda e^+\nu_e$		$(2.0 \pm 0.5) \times 10^{-5}$		71
$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 1$ weak neutral current ($S1$) modes				
$ne^+\nu_e$	SQ	$< 5 \times 10^{-6}$	90%	224
$n\mu^+\nu_\mu$	SQ	$< 3.0 \times 10^{-5}$	90%	202
pe^+e^-	$S1$	$< 7 \times 10^{-6}$		225

Σ^0

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1192.642 \pm 0.024$ MeV
$m_{\Sigma^-} - m_{\Sigma^0} = 4.807 \pm 0.035$ MeV (S = 1.1)
$m_{\Sigma^0} - m_\Lambda = 76.959 \pm 0.023$ MeV
Mean life $\tau = (7.4 \pm 0.7) \times 10^{-20}$ s
$c\tau = 2.22 \times 10^{-11}$ m
Transition magnetic moment $|\mu_{\Sigma\Lambda}| = 1.61 \pm 0.08\ \mu_N$

Σ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\gamma$		100 %		74
$\Lambda\gamma\gamma$		< 3 %	90%	74
Λe^+e^-	[j]	5×10^{-3}		74

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1197.449 \pm 0.030$ MeV (S = 1.2)
$m_{\Sigma^-} - m_{\Sigma^+} = 8.08 \pm 0.08$ MeV (S = 1.9)
$m_{\Sigma^-} - m_{\Lambda} = 81.766 \pm 0.030$ MeV (S = 1.2)
Mean life $\tau = (1.479 \pm 0.011) \times 10^{-10}$ s (S = 1.3)
$c\tau = 4.434$ cm
Magnetic moment $\mu = -1.160 \pm 0.025\ \mu_N$ (S = 1.7)

Decay parameters

$n\pi^-$	$\alpha_- = -0.068 \pm 0.008$
"	$\phi_- = (10 \pm 15)^\circ$
"	$\gamma_- = 0.98$ [g]
"	$\Delta_- = (249^{+12}_{-120})^\circ$ [g]
$ne^-\overline{\nu}_e$	$g_A/g_V = 0.340 \pm 0.017$ [e]
"	$f_2(0)/f_1(0) = 0.97 \pm 0.14$
"	$D = 0.11 \pm 0.10$
$\Lambda e^-\overline{\nu}_e$	$g_V/g_A = 0.01 \pm 0.10$ [e] (S = 1.5)
"	$g_{WM}/g_A = 2.4 \pm 1.7$ [e]

Σ^- DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$n\pi^-$	(99.848 ± 0.005) %	193
$n\pi^-\gamma$	[h] $(4.6 \pm 0.6) \times 10^{-4}$	193
$ne^-\overline{\nu}_e$	$(1.017 \pm 0.034) \times 10^{-3}$	230
$n\mu^-\overline{\nu}_\mu$	$(4.5 \pm 0.4) \times 10^{-4}$	210
$\Lambda e^-\overline{\nu}_e$	$(5.73 \pm 0.27) \times 10^{-5}$	79

$\Sigma(1385)\ P_{13}$

$I(J^P) = 1(\frac{3}{2}^+)$

$\Sigma(1385)^+$mass $m = 1382.8 \pm 0.4$ MeV (S = 2.0)
$\Sigma(1385)^0$ mass $m = 1383.7 \pm 1.0$ MeV (S = 1.4)
$\Sigma(1385)^-$mass $m = 1387.2 \pm 0.5$ MeV (S = 2.2)
$\Sigma(1385)^+$full width $\Gamma = 35.8 \pm 0.8$ MeV
$\Sigma(1385)^0$ full width $\Gamma = 36 \pm 5$ MeV
$\Sigma(1385)^-$full width $\Gamma = 39.4 \pm 2.1$ MeV (S = 1.7)
Below $\overline{K}N$ threshold

$\Sigma(1385)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\pi$	88 ± 2 %	208
$\Sigma\pi$	12 ± 2 %	127

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1630$ to 1690 (≈ 1660) MeV
Full width $\Gamma = 40$ to 200 (≈ 100) MeV
$p_{\text{beam}} = 0.72$ GeV/c $4\pi\lambda\!\!\!^{-2} = 29.9$ mb

$\Sigma(1660)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–30 %	405
$\Lambda\pi$	seen	439
$\Sigma\pi$	seen	385

$\Sigma(1670)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass $m = 1665$ to 1685 (≈ 1670) MeV
Full width $\Gamma = 40$ to 80 (≈ 60) MeV
$p_{\text{beam}} = 0.74$ GeV/c $4\pi\lambda\!\!\!^{-2} = 28.5$ mb

$\Sigma(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	7–13 %	414
$\Lambda\pi$	5–15 %	447
$\Sigma\pi$	30–60 %	393

$\Sigma(1750)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$

Mass $m = 1730$ to 1800 (≈ 1750) MeV
Full width $\Gamma = 60$ to 160 (≈ 90) MeV
$p_{\text{beam}} = 0.91$ GeV/c $4\pi\lambda\!\!\!^{-2} = 20.7$ mb

$\Sigma(1750)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–40 %	486
$\Lambda\pi$	seen	507
$\Sigma\pi$	<8 %	455
$\Sigma\eta$	15–55 %	81

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$

Mass $m = 1770$ to 1780 (≈ 1775) MeV
Full width $\Gamma = 105$ to 135 (≈ 120) MeV
$p_{\text{beam}} = 0.96$ GeV/c $4\pi\lambda\!\!\!^{-2} = 19.0$ mb

$\Sigma(1775)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	37–43%	508
$\Lambda\pi$	14–20%	525
$\Sigma\pi$	2–5%	474
$\Sigma(1385)\pi$	8–12%	324
$\Lambda(1520)\pi$	17–23%	198

$\Sigma(1915)\ F_{15}$

$I(J^P) = 1(\frac{5}{2}^+)$

Mass $m = 1900$ to 1935 (≈ 1915) MeV
Full width $\Gamma = 80$ to 160 (≈ 120) MeV
$p_{\text{beam}} = 1.26$ GeV/c $4\pi\lambda\!\!\!^{-2} = 12.8$ mb

$\Sigma(1915)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–15 %	618
$\Lambda\pi$	seen	622
$\Sigma\pi$	seen	577
$\Sigma(1385)\pi$	<5 %	440

$\Sigma(1940)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass $m = 1900$ to 1950 (≈ 1940) MeV
Full width $\Gamma = 150$ to 300 (≈ 220) MeV
$p_{\text{beam}} = 1.32$ GeV/c $4\pi\lambda\!\!\!^{-2} = 12.1$ mb

$\Sigma(1940)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<20 %	637
$\Lambda\pi$	seen	639
$\Sigma\pi$	seen	594
$\Sigma(1385)\pi$	seen	460
$\Lambda(1520)\pi$	seen	354
$\Delta(1232)\overline{K}$	seen	410
$N\overline{K}^*(892)$	seen	320

$\Sigma(2030)\ F_{17}$

$I(J^P) = 1(\frac{7}{2}^+)$

Mass $m = 2025$ to 2040 (≈ 2030) MeV
Full width $\Gamma = 150$ to 200 (≈ 180) MeV
$p_{\text{beam}} = 1.52$ GeV/c $4\pi\lambda\!\!\!^{-2} = 9.93$ mb

$\Sigma(2030)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	17–23 %	702
$\Lambda\pi$	17–23 %	700
$\Sigma\pi$	5–10 %	657
ΞK	<2 %	412
$\Sigma(1385)\pi$	5–15 %	529
$\Lambda(1520)\pi$	10–20 %	430
$\Delta(1232)\overline{K}$	10–20 %	498
$N\overline{K}^*(892)$	<5 %	438

$\Sigma(2250)$

$I(J^P) = 1(?^?)$

Mass $m = 2210$ to 2280 (≈ 2250) MeV
Full width $\Gamma = 60$ to 150 (≈ 100) MeV
$p_{\mathrm{beam}} = 2.04$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 6.76$ mb

$\Sigma(2250)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<10 %	851
$\Lambda\pi$	seen	842
$\Sigma\pi$	seen	803

Ξ BARYONS
$(S=-2, I=1/2)$

$\Xi^0 = uss, \quad \Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P is not yet measured; + is the quark model prediction.

Mass $m = 1314.9 \pm 0.6$ MeV
$m_{\Xi^-} - m_{\Xi^0} = 6.4 \pm 0.6$ MeV
Mean life $\tau = (2.90 \pm 0.09) \times 10^{-10}$ s
$c\tau = 8.71$ cm
Magnetic moment $\mu = -1.250 \pm 0.014\ \mu_N$

Decay parameters

$\Lambda\pi^0$ $\quad \alpha = -0.411 \pm 0.022 \quad (S = 2.1)$
" $\quad \phi = (21 \pm 12)^\circ$
" $\quad \gamma = 0.85$ [g]
" $\quad \Delta = (218^{+12}_{-19})^\circ$ [g]
$\Lambda\gamma$ $\quad \alpha = 0.4 \pm 0.4$
$\Sigma^0\gamma$ $\quad \alpha = 0.20 \pm 0.32$

Ξ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^0$		(99.54 ± 0.05) %		135
$\Lambda\gamma$		$(1.06 \pm 0.16) \times 10^{-3}$		184
$\Sigma^0\gamma$		$(3.5 \pm 0.4) \times 10^{-3}$		117
$\Sigma^+ e^- \overline{\nu}_e$		$< 1.1 \times 10^{-3}$	90%	120
$\Sigma^+ \mu^- \overline{\nu}_\mu$		$< 1.1 \times 10^{-3}$	90%	64
$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 2$ forbidden ($S2$) modes				
$\Sigma^- e^+ \nu_e$	SQ	$< 9 \times 10^{-4}$	90%	112
$\Sigma^- \mu^+ \nu_\mu$	SQ	$< 9 \times 10^{-4}$	90%	49
$p\pi^-$	$S2$	$< 4 \times 10^{-5}$	90%	299
$p e^- \overline{\nu}_e$	$S2$	$< 1.3 \times 10^{-3}$		323
$p \mu^- \overline{\nu}_\mu$	$S2$	$< 1.3 \times 10^{-3}$		309

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P is not yet measured; + is the quark model prediction.

Mass $m = 1321.32 \pm 0.13$ MeV
Mean life $\tau = (1.639 \pm 0.015) \times 10^{-10}$ s
$c\tau = 4.91$ cm
Magnetic moment $\mu = -0.6507 \pm 0.0025\ \mu_N$

Decay parameters

$\Lambda\pi^-$ $\quad \alpha = -0.456 \pm 0.014 \quad (S = 1.8)$
" $\quad \phi = (4 \pm 4)^\circ$
" $\quad \gamma = 0.89$ [g]
" $\quad \Delta = (188 \pm 8)^\circ$ [g]
$\Lambda e^- \overline{\nu}_e$ $\quad g_A/g_V = -0.25 \pm 0.05$ [e]

Ξ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^-$		(99.887 ± 0.035) %		139
$\Sigma^-\gamma$		$(1.27 \pm 0.23) \times 10^{-4}$		118
$\Lambda e^- \overline{\nu}_e$		$(5.63 \pm 0.31) \times 10^{-4}$		190
$\Lambda \mu^- \overline{\nu}_\mu$		$(3.5\ ^{+3.5}_{-2.2}) \times 10^{-4}$		163
$\Sigma^0 e^- \overline{\nu}_e$		$(8.7 \pm 1.7) \times 10^{-5}$		122
$\Sigma^0 \mu^- \overline{\nu}_\mu$		$< 8 \times 10^{-4}$	90%	70
$\Xi^0 e^- \overline{\nu}_e$		$< 2.3 \times 10^{-3}$	90%	6
$\Delta S = 2$ forbidden ($S2$) modes				
$n\pi^-$	$S2$	$< 1.9 \times 10^{-5}$	90%	303
$n e^- \overline{\nu}_e$	$S2$	$< 3.2 \times 10^{-3}$	90%	327
$n \mu^- \overline{\nu}_\mu$	$S2$	< 1.5 %	90%	314
$p\pi^-\pi^-$	$S2$	$< 4 \times 10^{-4}$	90%	223
$p\pi^- e^- \overline{\nu}_e$	$S2$	$< 4 \times 10^{-4}$	90%	304
$p\pi^- \mu^- \overline{\nu}_\mu$	$S2$	$< 4 \times 10^{-4}$	90%	250
$p\mu^-\mu^-$	L	$< 4 \times 10^{-4}$	90%	272

$\Xi(1530)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

$\Xi(1530)^0$ mass $m = 1531.80 \pm 0.32$ MeV $\quad (S = 1.3)$
$\Xi(1530)^-$ mass $m = 1535.0 \pm 0.6$ MeV
$\Xi(1530)^0$ full width $\Gamma = 9.1 \pm 0.5$ MeV
$\Xi(1530)^-$ full width $\Gamma = 9.9^{+1.7}_{-1.9}$ MeV

$\Xi(1530)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Xi\pi$	100 %		152
$\Xi\gamma$	<4 %	90%	200

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1690 \pm 10$ MeV [l]
Full width $\Gamma < 50$ MeV

$\Xi(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	240
$\Sigma\overline{K}$	seen	51
$\Xi^-\pi^+\pi^-$	possibly seen	214

$\Xi(1820)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass $m = 1823 \pm 5$ MeV [l]
Full width $\Gamma = 24^{+15}_{-10}$ MeV [l]

$\Xi(1820)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	large	400
$\Sigma\overline{K}$	small	320
$\Xi\pi$	small	413
$\Xi(1530)\pi$	small	234

$\Xi(1950)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1950 \pm 15$ MeV [l]
Full width $\Gamma = 60 \pm 20$ MeV [l]

$\Xi(1950)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	522
$\Sigma\overline{K}$	possibly seen	460
$\Xi\pi$	seen	518

$\Xi(2030)$

$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$

Mass $m = 2025 \pm 5$ MeV [l]
Full width $\Gamma = 20^{+15}_{-5}$ MeV [l]

$\Xi(2030)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	~ 20 %	589
$\Sigma\overline{K}$	~ 80 %	533
$\Xi\pi$	small	573
$\Xi(1530)\pi$	small	421
$\Lambda\overline{K}\pi$	small	501
$\Sigma\overline{K}\pi$	small	430

Ω BARYONS
$(S=-3, I=0)$

$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$

J^P is not yet measured; $\frac{3}{2}^+$ is the quark model prediction.

Mass $m = 1672.45 \pm 0.29$ MeV
Mean life $\tau = (0.822 \pm 0.012) \times 10^{-10}$ s
$c\tau = 2.46$ cm
Magnetic moment $\mu = -2.02 \pm 0.05\ \mu_N$

Decay parameters

ΛK^- $\alpha = -0.026 \pm 0.026$
$\Xi^0\pi^-$ $\alpha = 0.09 \pm 0.14$
$\Xi^-\pi^0$ $\alpha = 0.05 \pm 0.21$

Ω^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
ΛK^-		(67.8 ± 0.7) %		211
$\Xi^0\pi^-$		(23.6 ± 0.7) %		294
$\Xi^-\pi^0$		(8.6 ± 0.4) %		290
$\Xi^-\pi^+\pi^-$		$(4.3^{+3.4}_{-1.3}) \times 10^{-4}$		190
$\Xi(1530)^0\pi^-$		$(6.4^{+5.1}_{-2.0}) \times 10^{-4}$		17
$\Xi^0 e^-\overline{\nu}_e$		$(5.6\pm2.8) \times 10^{-3}$		319
$\Xi^-\gamma$		$< 4.6 \times 10^{-4}$	90%	314
$\Delta S = 2$ forbidden ($S2$) modes				
$\Lambda\pi^-$	$S2$	$< 1.9 \times 10^{-4}$	90%	449

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$

Mass $m = 2252 \pm 9$ MeV
Full width $\Gamma = 55 \pm 18$ MeV

$\Omega(2250)^-$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi^-\pi^+K^-$	seen	531
$\Xi(1530)^0K^-$	seen	437

CHARMED BARYONS
$(C=+1)$

$\Lambda_c^+ = udc,\quad \Sigma_c^{++} = uuc,\quad \Sigma_c^+ = udc,\quad \Sigma_c^0 = ddc,$
$\Xi_c^+ = usc,\quad \Xi_c^0 = dsc,\quad \Omega_c^0 = ssc$

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$

J not confirmed; $\frac{1}{2}$ is the quark model prediction.

Mass $m = 2284.9 \pm 0.6$ MeV
Mean life $\tau = (0.206 \pm 0.012) \times 10^{-12}$ s
$c\tau = 61.8\ \mu$m

Decay asymmetry parameters

$\Lambda\pi^+$ $\alpha = -0.98 \pm 0.19$
$\Sigma^+\pi^0$ $\alpha = -0.45 \pm 0.32$
$\Lambda\ell^+\nu_\ell$ $\alpha = -0.82^{+0.11}_{-0.07}$

Nearly all branching fractions of the Λ_c^+ are measured relative to the $pK^-\pi^+$ mode, but there are no model-independent measurements of this branching fraction. We explain how we arrive at our value of $B(\Lambda_c^+ \to pK^-\pi^+)$ in a Note at the beginning of the branching-ratio measurements, in the Listings. When this branching fraction is eventually well determined, all the other branching fractions will slide up or down proportionally as the true value differs from the value we use here.

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p and one $\overline{K}$				
$p\overline{K}^0$		(2.5 ± 0.7) %		872
$pK^-\pi^+$	[k]	(5.0 ± 1.3) %		822
$p\overline{K}^*(892)^0$	[l]	(1.8 ± 0.6) %		681
$\Delta(1232)^{++}K^-$		$(8 \pm 5) \times 10^{-3}$		709
$\Lambda(1520)\pi^+$	[l]	$(4.5\ ^{+2.5}_{-2.1}) \times 10^{-3}$		626
$pK^-\pi^+$ nonresonant		(2.8 ± 0.9) %		822
$p\overline{K}^0\eta$		(1.3 ± 0.4) %		567
$p\overline{K}^0\pi^+\pi^-$		(2.4 ± 1.1) %		753
$pK^-\pi^+\pi^0$		seen		758
$pK^*(892)^-\pi^+$	[l]	(1.1 ± 0.6) %		579
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(3.6 ± 1.2) %		758
$\Delta(1232)\overline{K}^*(892)$		seen		416
$pK^-\pi^+\pi^+\pi^-$		$(1.1 \pm 0.8) \times 10^{-3}$		670
$pK^-\pi^+\pi^0\pi^0$		$(8 \pm 4) \times 10^{-3}$		676
$pK^-\pi^+\pi^0\pi^0\pi^0$		$(5.0 \pm 3.4) \times 10^{-3}$		573
Hadronic modes with a p and zero or two K's				
$p\pi^+\pi^-$		$(3.5 \pm 2.0) \times 10^{-3}$		926
$pf_0(980)$	[l]	$(2.8 \pm 1.9) \times 10^{-3}$		621
$p\pi^+\pi^+\pi^-\pi^-$		$(1.8 \pm 1.2) \times 10^{-3}$		851
pK^+K^-		$(2.3 \pm 0.9) \times 10^{-3}$		615
$p\phi$	[l]	$(1.2 \pm 0.5) \times 10^{-3}$		589
Hadronic modes with a hyperon				
$\Lambda\pi^+$		$(9.0 \pm 2.8) \times 10^{-3}$		863
$\Lambda\pi^+\pi^0$		(3.6 ± 1.3) %		843
$\Lambda\rho^+$		< 5 %	CL=95%	638
$\Lambda\pi^+\pi^+\pi^-$		(3.3 ± 1.0) %		806
$\Lambda\pi^+\eta$		(1.7 ± 0.6) %		690
$\Sigma(1385)^+\eta$	[l]	$(8.5 \pm 3.3) \times 10^{-3}$		569
$\Lambda K^+\overline{K}^0$		$(6.0 \pm 2.1) \times 10^{-3}$		441
$\Sigma^0\pi^+$		$(9.9 \pm 3.2) \times 10^{-3}$		824
$\Sigma^+\pi^0$		(1.00 ± 0.34) %		826
$\Sigma^+\eta$		$(5.5 \pm 2.3) \times 10^{-3}$		712
$\Sigma^+\pi^+\pi^-$		(3.4 ± 1.0) %		803
$\Sigma^+\rho^0$		< 1.4 %	CL=95%	578
$\Sigma^-\pi^+\pi^+$		(1.8 ± 0.8) %		798
$\Sigma^0\pi^+\pi^0$		(1.8 ± 0.8) %		802
$\Sigma^0\pi^+\pi^+\pi^-$		(1.1 ± 0.4) %		762
$\Sigma^+\pi^+\pi^-\pi^0$		—		766
$\Sigma^+\omega$	[l]	(2.7 ± 1.0) %		568
$\Sigma^+\pi^+\pi^+\pi^-\pi^-$		$(3.0\ ^{+4.1}_{-2.1}) \times 10^{-3}$		707
$\Sigma^+K^+K^-$		$(3.5 \pm 1.2) \times 10^{-3}$		346
$\Sigma^+\phi$	[l]	$(3.5 \pm 1.7) \times 10^{-3}$		292
$\Sigma^+K^+\pi^-$		$(7\ ^{+6}_{-4}) \times 10^{-3}$		668
Ξ^0K^+		$(3.9 \pm 1.4) \times 10^{-3}$		652
$\Xi^-K^+\pi^+$		$(4.9 \pm 1.7) \times 10^{-3}$		564
$\Xi(1530)^0K^+$	[l]	$(2.6 \pm 1.0) \times 10^{-3}$		471
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[m]	(2.0 ± 0.6) %		–
$\Lambda e^+\nu_e$		(2.1 ± 0.6) %		–
$\Lambda\mu^+\nu_\mu$		(2.0 ± 0.7) %		–
e^+anything		(4.5 ± 1.7) %		–
pe^+anything		(1.8 ± 0.9) %		–
Λe^+anything		—		–
$\Lambda\mu^+$anything		—		–
$\Lambda\ell^+\nu_\ell$anything		—		–
Inclusive modes				
p anything		(50 ± 16) %		–
p anything (no Λ)		(12 ± 19) %		–
p hadrons		—		–
n anything		(50 ± 16) %		–
n anything (no Λ)		(29 ± 17) %		–
Λ anything		(35 ± 11) %	S=1.4	–
$\Sigma^\pm$anything	[n]	(10 ± 5) %		–

$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes

$p\mu^+\mu^-$	$C1$	< 3.4	$\times 10^{-4}$	CL=90%	936
$\Sigma^-\mu^+\mu^+$	L	< 7.0	$\times 10^{-4}$	CL=90%	811

$\Lambda_c(2593)^+$

$I(J^P) = 0(\frac{1}{2}^-)$

The spin-parity follows from the fact that $\Sigma_c(2455)\pi$ decays, with little available phase space, are dominant.

Mass $m = 2593.9 \pm 0.8$ MeV
$m - m_{\Lambda_c^+} = 308.9 \pm 0.6$ MeV (S = 1.1)
Full width $\Gamma = 3.6^{+2.0}_{-1.3}$ MeV

$\Lambda_c^+\pi\pi$ and its submode $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the $\Lambda_c^+\pi^+\pi^-$ mode seems to be largely via $\Sigma_c^{++}\pi^-$ or $\Sigma_c^0\pi^+$.

$\Lambda_c(2593)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	[o] ≈ 67 %	124
$\Sigma_c(2455)^{++}\pi^-$	24 ± 7 %	17
$\Sigma_c(2455)^0\pi^+$	24 ± 7 %	23
$\Lambda_c^+\pi^+\pi^-$ 3-body	18 ± 10 %	124
$\Lambda_c^+\pi^0$	not seen	261
$\Lambda_c^+\gamma$	not seen	290

$\Lambda_c(2625)^+$

$I(J^P) = 0(?^?)$

J^P is expected to be $3/2^-$.

Mass $m = 2626.6 \pm 0.8$ MeV (S = 1.2)
$m - m_{\Lambda_c^+} = 341.7 \pm 0.6$ MeV (S = 1.6)
Full width $\Gamma < 1.9$ MeV, CL = 90%

$\Lambda_c^+\pi\pi$ and its submode $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

$\Lambda_c(2625)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	seen	184
$\Sigma_c(2455)^{++}\pi^-$	small	100
$\Sigma_c(2455)^0\pi^+$	small	101
$\Lambda_c^+\pi^+\pi^-$ 3-body	large	184
$\Lambda_c^+\pi^0$	not seen	293
$\Lambda_c^+\gamma$	not seen	319

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not confirmed; $\frac{1}{2}^+$ is the quark model prediction.

$\Sigma_c(2455)^{++}$ mass $m = 2452.8 \pm 0.6$ MeV
$\Sigma_c(2455)^+$ mass $m = 2453.6 \pm 0.9$ MeV
$\Sigma_c(2455)^0$ mass $m = 2452.2 \pm 0.6$ MeV
$m_{\Sigma_c^{++}} - m_{\Lambda_c^+} = 167.87 \pm 0.19$ MeV
$m_{\Sigma_c^+} - m_{\Lambda_c^+} = 168.7 \pm 0.6$ MeV
$m_{\Sigma_c^0} - m_{\Lambda_c^+} = 167.30 \pm 0.20$ MeV
$m_{\Sigma_c^{++}} - m_{\Sigma_c^0} = 0.57 \pm 0.23$ MeV
$m_{\Sigma_c^+} - m_{\Sigma_c^0} = 1.4 \pm 0.6$ MeV

$\Lambda_c^+\pi$ is the only strong decay allowed to a Σ_c having this mass.

$\Sigma_c(2455)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi$	≈ 100 %	90

$\Sigma_c(2520)$

$I(J^P) = 1(?^?)$

$\Sigma_c(2520)^{++}$ mass $m = 2519.4 \pm 1.5$ MeV
$\Sigma_c(2520)^0$ mass $m = 2517.5 \pm 1.4$ MeV
$m_{\Sigma_c(2520)^{++}} - m_{\Lambda_c^+} = 234.5 \pm 1.4$ MeV
$m_{\Sigma_c(2520)^0} - m_{\Lambda_c^+} = 232.6 \pm 1.3$ MeV
$m_{\Sigma_c(2520)^{++}} - m_{\Sigma_c(2520)^0} = 1.9 \pm 1.9$ MeV
$\Sigma_c(2520)^{++}$ full width $\Gamma = 18 \pm 5$ MeV
$\Sigma_c(2520)^0$ full width $\Gamma = 13 \pm 5$ MeV

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2465.6 \pm 1.4$ MeV
Mean life $\tau = (0.35^{+0.07}_{-0.04}) \times 10^{-12}$ s
$c\tau = 106$ μm

Ξ_c^+ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda K^-\pi^+\pi^+$	seen	784
$\Lambda\overline{K}^*(892)^0\pi^+$	not seen	601
$\Sigma(1385)^+K^-\pi^+$	not seen	676
$\Sigma^+K^-\pi^+$	seen	808
$\Sigma^+\overline{K}^*(892)^0$	seen	653
$\Sigma^0K^-\pi^+\pi^+$	seen	733
$\Xi^0\pi^+$	seen	875
$\Xi^-\pi^+\pi^+$	seen	850
$\Xi(1530)^0\pi^+$	not seen	748
$\Xi^0\pi^+\pi^0$	seen	854
$\Xi^0\pi^+\pi^+\pi^-$	seen	817
$\Xi^0e^+\nu_e$	seen	882

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2470.3 \pm 1.8$ MeV (S = 1.3)
$m_{\Xi_c^0} - m_{\Xi_c^+} = 4.7 \pm 2.1$ MeV (S = 1.2)
Mean life $\tau = (0.098^{+0.023}_{-0.015}) \times 10^{-12}$ s
$c\tau = 29$ μm

Ξ_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}^0$	seen	864
$\Xi^-\pi^+$	seen	875
$\Xi^-\pi^+\pi^+\pi^-$	seen	816
$pK^-\overline{K}^*(892)^0$	seen	406
Ω^-K^+	seen	522
$\Xi^-e^+\nu_e$	seen	882
$\Xi^-\ell^+$ anything	seen	–

$\Xi_c(2645)$

$I(J^P) = ?(?^?)$

$\Xi_c(2645)^+$ mass $m = 2644.6 \pm 2.1$ MeV (S = 1.2)
$\Xi_c(2645)^0$ mass $m = 2643.8 \pm 1.8$ MeV
$m_{\Xi_c(2645)^+} - m_{\Xi_c^0} = 174.3 \pm 1.1$ MeV
$m_{\Xi_c(2645)^0} - m_{\Xi_c^+} = 178.2 \pm 1.1$ MeV
$\Xi_c(2645)^+$ full width $\Gamma < 3.1$ MeV, CL = 90%
$\Xi_c(2645)^0$ full width $\Gamma < 5.5$ MeV, CL = 90%

$\Xi_c\pi$ is the only strong decay allowed to a Ξ_c resonance having this mass.

$\Xi_c(2645)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi_c^0\pi^+$	seen	101
$\Xi_c^+\pi^-$	seen	107

Ω_c^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2704 \pm 4$ MeV (S = 1.8)
Mean life $\tau = (0.064 \pm 0.020) \times 10^{-12}$ s
$c\tau = 19\ \mu$m

Ω_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma^+ K^- K^- \pi^+$	seen	697
$\Xi^- K^- \pi^+ \pi^+$	seen	838
$\Omega^- \pi^+$	seen	827
$\Omega^- \pi^- \pi^+ \pi^+$	seen	759

BOTTOM BARYONS
$(B = -1)$

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 5624 \pm 9$ MeV (S = 1.8)
Mean life $\tau = (1.24 \pm 0.08) \times 10^{-12}$ s
$c\tau = 372\ \mu$m

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction $B(b \to \Lambda_b)$ and are evaluated for our value $B(b \to \Lambda_b) = (10.1^{+3.9}_{-3.1})\%$.

The branching fractions $B(b\text{-baryon} \to \Lambda \ell^- \overline{\nu}_\ell \text{anything})$ and $B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything})$ are not pure measurements because the underlying measured products of these with $B(b \to \Lambda_b)$ were used to determine $B(b \to \Lambda_b)$, as described in the note "Production and Decay of b-Flavored Hadrons."

Λ_b^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\Lambda$		$(4.7\pm2.8) \times 10^{-4}$		1744
$\Lambda_c^+ \pi^-$		seen		2345
$\Lambda_c^+ a_1(1260)^-$		seen		2156
$\Lambda_c^+ \ell^- \overline{\nu}_\ell$anything	[p]	$(9.0^{+3.1}_{-3.8})$ %		–
$p\pi^-$		$< 5.0 \times 10^{-5}$	90%	2732
pK^-		$< 5.0 \times 10^{-5}$	90%	2711

b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b)

Mean life $\tau = (1.20 \pm 0.07) \times 10^{-12}$ s

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction $B(b \to \Lambda_b)$ and are evaluated for our value $B(b \to \Lambda_b) = (10.1^{+3.9}_{-3.1})\%$.

The branching fractions $B(b\text{-baryon} \to \Lambda \ell^- \overline{\nu}_\ell \text{anything})$ and $B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything})$ are not pure measurements because the underlying measured products of these with $B(b \to \Lambda_b)$ were used to determine $B(b \to \Lambda_b)$, as described in the note "Production and Decay of b-Flavored Hadrons."

b-baryon ADMIXTURE (Λ_b,Ξ_b,Σ_b,Ω_b)	Fraction (Γ_i/Γ)	p (MeV/c)
$p \mu^- \overline{\nu}$anything	(4.9 ± 2.4) %	–
$\Lambda \ell^- \overline{\nu}_\ell$anything	$(3.1^{+1.0}_{-1.2})$ %	–
$\Lambda/\overline{\Lambda}$anything	(35^{+12}_{-14}) %	–
$\Xi^- \ell^- \overline{\nu}_\ell$anything	$(5.5^{+2.0}_{-2.4}) \times 10^{-3}$	–

NOTES

This Summary Table only includes established baryons. The Particle Listings include evidence for other baryons. The masses, widths, and branching fractions for the resonances in this Table are Breit-Wigner parameters, but pole positions are also given for most of the N and Δ resonances.

For most of the resonances, the parameters come from various partial-wave analyses of more or less the same sets of data, and it is not appropriate to treat the results of the analyses as independent or to average them together. Furthermore, the systematic errors on the results are not well understood. Thus, we usually only give ranges for the parameters. We then also give a best guess for the mass (as part of the name of the resonance) and for the width. The *Note on N and Δ Resonances* and the *Note on Λ and Σ Resonances* in the Particle Listings review the partial-wave analyses.

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when $S > 1$, which often indicates that the measurements are inconsistent. When $S > 1.25$, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame. For any resonance, the *nominal* mass is used in calculating p. A dagger ("†") in this column indicates that the mode is forbidden when the nominal masses of resonances are used, but is in fact allowed due to the nonzero widths of the resonances.

[a] The masses of the p and n are most precisely known in u (unified atomic mass units). The conversion factor to MeV, 1 u = 931.49432 ± 0.00028 MeV, is less well known than are the masses in u.

[b] The limit is from neutrality-of-matter experiments; it assumes $q_n = q_p + q_e$. See also the charge of the neutron.

[c] The first limit is geochemical and independent of decay mode. The second entry, a range of limits, assumes the dominant decay modes are among those investigated. For antiprotons the best limit, inferred from the observation of cosmic ray $\overline{p}$'s is $\tau_{\overline{p}} > 10^7$ yr, the cosmic-ray storage time, but this limit depends on a number of assumptions. The best direct observation of stored antiprotons gives $\tau_{\overline{p}}/B(\overline{p} \to e^- \gamma) > 1848$ yr.

[d] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The second limit here is from reactor experiments with free neutrons.

[e] The parameters g_A, g_V, and g_{WM} for semileptonic modes are defined by $\overline{B}_f[\gamma_\lambda(g_V + g_A\gamma_5) + i(g_{WM}/m_{B_i})\,\sigma_{\lambda\nu}\, q^\nu]B_i$, and ϕ_{AV} is defined by $g_A/g_V = |g_A/g_V| e^{i\phi_{AV}}$. See the "Note on Baryon Decay Parameters" in the neutron Particle Listings.

[f] Time-reversal invariance requires this to be 0° or 180°.

[g] The decay parameters γ and Δ are calculated from α and ϕ using

$$\gamma = \sqrt{1-\alpha^2}\,\cos\phi\,, \qquad \tan\Delta = -\frac{1}{\alpha}\,\sqrt{1-\alpha^2}\,\sin\phi\,.$$

See the "Note on Baryon Decay Parameters" in the neutron Particle Listings.

[h] See the Particle Listings for the pion momentum range used in this measurement.

[i] The error given here is only an educated guess. It is larger than the error on the weighted average of the published values.

[j] A theoretical value using QED.

[k] See the "Note on Λ_c^+ Branching Fractions" in the Branching Fractions of the Λ_c^+ Particle Listings.

[l] This branching fraction includes all the decay modes of the final-state resonance.

[m] An ℓ indicates an e or a μ mode, not a sum over these modes.

[n] The value is for the sum of the charge states of particle/antiparticle states indicated.

[o] Assuming isospin conservation, so that the other third is $\Lambda_c^+ \pi^0 \pi^0$.

[p] Not a pure measurement. See note at head of Λ_b^0 Decay Modes.

MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc., SEARCHES FOR

Magnetic Monopole Searches

Isolated supermassive monopole candidate events have not been confirmed. The most sensitive experiments obtain negative results.

Best cosmic-ray supermassive monopole flux limit:
$< 1.0 \times 10^{-15}$ cm^{-2}sr^{-1}s^{-1} for $1.1 \times 10^{-4} < \beta < 0.1$

Supersymmetric Particle Searches

Limits are based on the Minimal Supersymmetric Standard Model.

Assumptions include: 1) $\widetilde{\chi}^0_1$ (or $\widetilde{\gamma}$) is lightest supersymmetric particle; 2) R-parity is conserved; 3) All scalar quarks (except $\widetilde{t}_L$ and $\widetilde{t}_R$) are degenerate in mass, and $m_{\widetilde{q}_R} = m_{\widetilde{q}_L}$. 4) Limits for selectrons and smuons refer to the $\widetilde{\ell}_R$ states.

See the Particle Listings for a Note giving details of supersymmetry.

$\widetilde{\chi}^0_i$ — neutralinos (mixtures of $\widetilde{\gamma}$, $\widetilde{Z}^0$, and $\widetilde{H}^0_i$)
Mass $m_{\widetilde{\chi}^0_1}$ > 10.9 GeV, CL = 95%
Mass $m_{\widetilde{\chi}^0_2}$ > 45.3 GeV, CL = 95% [tanβ >1]
Mass $m_{\widetilde{\chi}^0_3}$ > 75.8 GeV, CL = 95% [tanβ >1]
Mass $m_{\widetilde{\chi}^0_4}$ > 127 GeV, CL = 95% [tanβ >3]

$\widetilde{\chi}^{\pm}_i$ — charginos (mixtures of $\widetilde{W}^{\pm}$ and $\widetilde{H}^{\pm}_i$)
Mass $m_{\widetilde{\chi}^{\pm}_1}$ > 65.7 GeV, CL = 95% [$m_{\widetilde{\chi}^{\pm}_1} - m_{\widetilde{\chi}^0_1} \geq 2$ GeV]
Mass $m_{\widetilde{\chi}^{\pm}_2}$ > 99 GeV, CL = 95% [GUT relations assumed]

$\widetilde{\nu}$ — scalar neutrino (sneutrino)
Mass $m >$ 37.1 GeV, CL = 95% [one flavor]
Mass $m >$ 43.1 GeV, CL = 95% [three degenerate flavors]

$\widetilde{e}$ — scalar electron (selectron)
Mass $m >$ 58 GeV, CL = 95% [$m_{\widetilde{e}_R} - m_{\widetilde{\chi}^0_1} \geq 4$ GeV]

$\widetilde{\mu}$ — scalar muon (smuon)
Mass $m >$ 55.6 GeV, CL = 95% [$m_{\widetilde{\mu}_R} - m_{\widetilde{\chi}^0_1} \geq 4$ GeV]

$\widetilde{\tau}$ — scalar tau (stau)
Mass $m >$ 45 GeV, CL = 95% [if $m_{\widetilde{\chi}^0_1} < 38$ GeV]

$\widetilde{q}$ — scalar quark (squark)

These limits include the effects of cascade decays, evaluated assuming a fixed value of the parameters μ and tanβ. The limits are weakly sensitive to these parameters over much of parameter space. Limits assume GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}^0_1} \approx m_{\widetilde{g}}/6$.

Mass $m >$ 176 GeV, CL = 95% [any $m_{\widetilde{g}}$ <300 GeV, $\mu = -250$ GeV, tan$\beta = 2$]
Mass $m >$ 224 GeV, CL = 95% [$m_{\widetilde{g}} \leq m_{\widetilde{q}}$, $\mu = -400$ GeV, tan$\beta = 4$]

$\widetilde{g}$ — gluino

There is some controversy on whether gluinos in a low-mass window ($1 \lesssim m_{\widetilde{g}} \lesssim 5$ GeV) are excluded or not. See the Supersymmetry Listings for details.

The limits summarised here refere to the high-mass region ($m_{\widetilde{g}} \gtrsim 5$ GeV), and include the effects of cascade decays, evaluated assuming a fixed value of the parameters μ and tanβ. The limits are weakly sensitive to these parameters over much of parameter space. Limits assume GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}^0_1} \approx m_{\widetilde{g}}/6$.

Mass $m >$ 173 GeV, CL = 95% [any $m_{\widetilde{q}}$, $\mu = -200$ GeV, tan$\beta = 2$]
Mass $m >$ 212 GeV, CL = 95% [$m_{\widetilde{g}} \geq m_{\widetilde{q}}$, $\mu = -250$ GeV, tan$\beta = 2$]

Quark and Lepton Compositeness, Searches for

Scale Limits Λ for Contact Interactions (the lowest dimensional interactions with four fermions)

If the Lagrangian has the form

$$\pm \frac{g^2}{2\Lambda^2} \overline{\psi}_L \gamma_\mu \psi_L \overline{\psi}_L \gamma^\mu \psi_L$$

(with $g^2/4\pi$ set equal to 1), then we define $\Lambda \equiv \Lambda^{\pm}_{LL}$. For the full definitions and for other forms, see the Note in the Listings on Searches for Quark and Lepton Compositeness in the full *Review* and the original literature.

$\Lambda^{+}_{LL}(eeee)$ > 2.4 TeV, CL = 95%
$\Lambda^{-}_{LL}(eeee)$ > 3.6 TeV, CL = 95%
$\Lambda^{+}_{LL}(ee\mu\mu)$ > 2.6 TeV, CL = 95%
$\Lambda^{-}_{LL}(ee\mu\mu)$ > 2.9 TeV, CL = 95%
$\Lambda^{+}_{LL}(ee\tau\tau)$ > 1.9 TeV, CL = 95%
$\Lambda^{-}_{LL}(ee\tau\tau)$ > 3.0 TeV, CL = 95%
$\Lambda^{+}_{LL}(\ell\ell\ell\ell)$ > 3.5 TeV, CL = 95%
$\Lambda^{-}_{LL}(\ell\ell\ell\ell)$ > 3.8 TeV, CL = 95%
$\Lambda^{+}_{LL}(eeqq)$ > 2.5 TeV, CL = 95%
$\Lambda^{-}_{LL}(eeqq)$ > 3.7 TeV, CL = 95%
$\Lambda^{+}_{LL}(eebb)$ > 3.1 TeV, CL = 95%
$\Lambda^{-}_{LL}(eebb)$ > 2.9 TeV, CL = 95%
$\Lambda^{+}_{LL}(\mu\mu qq)$ > 2.9 TeV, CL = 95%
$\Lambda^{-}_{LL}(\mu\mu qq)$ > 4.2 TeV, CL = 95%
$\Lambda^{\pm}_{LR}(\nu_\mu \nu_e \mu e)$ > 3.1 TeV, CL = 90%
$\Lambda^{\pm}_{LL}(qqqq)$ > 1.6 TeV, CL = 95%

Excited Leptons

The limits from $\ell^{*+}\ell^{*-}$ do not depend on λ (where λ is the $\ell\ell^*$ transition coupling). The λ-dependent limits assume chiral coupling, except for the third limit for e^* which is for nonchiral coupling. For chiral coupling, this limit corresponds to $\lambda_\gamma = \sqrt{2}$.

$e^{*\pm}$ — excited electron
Mass $m >$ 85.0 GeV, CL = 95% (from $e^{*+}e^{*-}$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 1$)
Mass $m >$ 194 GeV, CL = 95% (if $\lambda_\gamma = 1$)

$\mu^{*\pm}$ — excited muon
Mass $m >$ 85.3 GeV, CL = 95% (from $\mu^{*+}\mu^{*-}$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 1$)

$\tau^{*\pm}$ — excited tau
Mass $m >$ 84.6 GeV, CL = 95% (from $\tau^{*+}\tau^{*-}$)
Mass $m >$ 90 GeV, CL = 95% (if $\lambda_Z > 0.18$)

ν^* — excited neutrino
Mass $m >$ 84.9 GeV, CL = 95% (from $\nu^* \overline{\nu}^*$)
Mass $m >$ 91 GeV, CL = 95% (if $\lambda_Z > 1$)
Mass m = none 40–96 GeV, CL = 95% (from $ep \rightarrow \nu^* X$)

q^* — excited quark
Mass $m >$ 45.6 GeV, CL = 95% (from $q^* \overline{q}^*$)
Mass $m >$ 88 GeV, CL = 95% (if $\lambda_Z > 1$)
Mass $m >$ 570 GeV, CL = 95% ($p\overline{p} \rightarrow q^* X$)

Color Sextet and Octet Particles

Color Sextet Quarks (q_6)
Mass $m >$ 84 GeV, CL = 95% (Stable q_6)

Color Octet Charged Leptons (ℓ_8)
Mass $m >$ 86 GeV, CL = 95% (Stable ℓ_8)

Color Octet Neutrinos (ν_8)
Mass $m >$ 110 GeV, CL = 90% ($\nu_8 \rightarrow \nu g$)

Tests of Conservation Laws

TESTS OF CONSERVATION LAWS

Revised by L. Wolfenstein and T.G. Trippe, May 1998.

In keeping with the current interest in tests of conservation laws, we collect together a Table of experimental limits on all weak and electromagnetic decays, mass differences, and moments, and on a few reactions, whose observation would violate conservation laws. The Table is given only in the full *Review of Particle Physics*, not in the Particle Physics Booklet. For the benefit of Booklet readers, we include the best limits from the Table in the following text. Limits in this text are for CL=90% unless otherwise specified. The Table is in two parts: "Discrete Space-Time Symmetries," *i.e.*, C, P, T, CP, and CPT; and "Number Conservation Laws," *i.e.*, lepton, baryon, hadronic flavor, and charge conservation. The references for these data can be found in the the Particle Listings in the *Review*. A discussion of these tests follows.

CPT INVARIANCE

General principles of relativistic field theory require invariance under the combined transformation CPT. The simplest tests of CPT invariance are the equality of the masses and lifetimes of a particle and its antiparticle. The best test comes from the limit on the mass difference between K^0 and $\overline{K}^0$. Any such difference contributes to the CP-violating parameter ϵ. Assuming CPT invariance, ϕ_ϵ, the phase of ϵ should be very close to 44°. (See the "Note on CP Violation in K^0_L Decay" in the Particle Listings.) In contrast, if the entire source of CP violation in K^0 decays were a $K^0 - \overline{K}^0$ mass difference, ϕ_ϵ would be $44° + 90°$. Assuming that there is no other source of CPT violation than this mass difference, it is possible to deduce that [1]

$$m_{\overline{K}^0} - m_{K^0} \approx \frac{2(m_{K^0_L} - m_{K^0_S})\,|\eta|\,(\frac{2}{3}\phi_{+-} + \frac{1}{3}\phi_{00} - \phi_0)}{\sin\phi_0}\,,$$

where $\phi_0 = 43.5°$ with an uncertainty of less than $0.1°$. Using our best values of the CP-violation parameters, we get $|(m_{\overline{K}^0} - m_{K^0})/m_{K^0}| \leq 10^{-18}$. Limits can also be placed on specific CPT-violating decay amplitudes. Given the small value of $(1 - |\eta_{00}/\eta_{+-}|)$, the value of $\phi_{00} - \phi_{+-}$ provides a measure of CPT violation in $K^0_L \to 2\pi$ decay. Results from CERN [1] and Fermilab [2] indicate no CPT-violating effect.

CP AND T INVARIANCE

Given CPT invariance, CP violation and T violation are equivalent. So far the only evidence for CP or T violation comes from the measurements of η_{+-}, η_{00}, and the semileptonic decay charge asymmetry for K_L, *e.g.*, $|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-)/A(K^0_S \to \pi^+\pi^-)| = (2.285 \pm 0.019) \times 10^{-3}$ and $[\Gamma(K^0_L \to \pi^- e^+ \nu) - \Gamma(K^0_L \to \pi^+ e^- \overline{\nu})]/[\text{sum}] = (0.333 \pm 0.014)\%$. Other searches for CP or T violation divide into (a) those that involve weak interactions or parity violation, and (b) those that involve processes otherwise allowed by the strong or electromagnetic interactions. In class (a) the most sensitive are probably the searches for an electric dipole moment of the neutron, measured to be $< 1.0 \times 10^{-25}$ e cm, and the electron $(-0.18 \pm 0.16) \times 10^{-26}$ e cm. A nonzero value requires both P and T violation. Class (b) includes the search for C violation in η decay, believed to be an electromagnetic process, *e.g.*, as measured by $\Gamma(\eta \to \mu^+\mu^-\pi^0)/\Gamma(\eta \to \text{all}) < 5 \times 10^{-6}$, and searches for T violation in a number of nuclear and electromagnetic reactions.

CONSERVATION OF LEPTON NUMBERS

Present experimental evidence and the standard electroweak theory are consistent with the absolute conservation of three separate lepton numbers: electron number L_e, muon number L_μ, and tau number L_τ. Searches for violations are of the following types:

a) $\Delta L = 2$ for one type of lepton. The best limit comes from the search for neutrinoless double beta decay $(Z, A) \to (Z + 2, A) + e^- + e^-$. The best laboratory limit is $t_{1/2} > 1.1 \times 10^{25}$ yr (CL=90%) for ^{76}Ge.

b) Conversion of one lepton type to another. For purely leptonic processes, the best limits are on $\mu \to e\gamma$ and $\mu \to 3e$, measured as $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \text{all}) < 5 \times 10^{-11}$ and $\Gamma(\mu \to 3e)/\Gamma(\mu \to \text{all}) < 1.0 \times 10^{-12}$. For semileptonic processes, the best limit comes from the coherent conversion process in a muonic atom, $\mu^- + (Z, A) \to e^- + (Z, A)$, measured as $\Gamma(\mu^-\text{Ti} \to e^-\text{Ti})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 4 \times 10^{-12}$. Of special interest is the case in which the hadronic flavor also changes, as in $K_L \to e\mu$ and $K^+ \to \pi^+ e^- \mu^+$, measured as $\Gamma(K_L \to e\mu)/\Gamma(K_L \to \text{all}) < 3.3 \times 10^{-11}$ and $\Gamma(K^+ \to \pi^+ e^- \mu^+)/\Gamma(K^+ \to \text{all}) < 2.1 \times 10^{-10}$. Limits on the conversion of τ into e or μ are found in τ decay and are much less stringent than those for $\mu \to e$ conversion, *e.g.*, $\Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \text{all}) < 3.0 \times 10^{-6}$ and $\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all}) < 2.7 \times 10^{-6}$.

c) Conversion of one type of lepton into another type of antilepton. The case most studied is $\mu^- + (Z, A) \to e^+ + (Z - 2, A)$, the strongest limit being $\Gamma(\mu^-\text{Ti} \to e^+\text{Ca})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 9 \times 10^{-11}$.

d) Relation to neutrino mass. If neutrinos have mass, then it is expected even in the standard electroweak theory that the lepton numbers are not separately conserved, as a consequence of lepton mixing analogous to Cabibbo quark mixing. However, in this case lepton-number-violating processes such as $\mu \to e\gamma$ are expected to have extremely small probability. For small neutrino masses, the lepton-number violation would be observed first in neutrino oscillations, which have been the subject of extensive experimental searches. For example, searches for $\overline{\nu}_e$ disappearance, which we label as $\overline{\nu}_e \not\to \overline{\nu}_e$, give measured limits $\Delta(m^2) < 9 \times 10^{-4}$ eV^2 for $\sin^2(2\theta) = 1$, and $\sin^2(2\theta) < 0.02$ for large $\Delta(m^2)$, where θ is the neutrino mixing angle. Possible evidence for mixing has come from two sources. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with $\Delta(m^2) \leq 10^{-5}$ eV^2 causing the disappearance of ν_e. In addition underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This could be explained by oscillations leading to the disappearance of ν_μ with $\Delta(m^2)$ of the order 10^{-2}–10^{-3} eV^2.

CONSERVATION OF HADRONIC FLAVORS

In strong and electromagnetic interactions, hadronic flavor is conserved, *i.e.* the conversion of a quark of one flavor (d, u, s, c, b, t) into a quark of another flavor is forbidden. In the Standard Model, the weak interactions violate these conservation laws in a manner described by the Cabibbo-Kobayashi-Maskawa mixing (see the section "Cabibbo-Kobayashi-Maskawa Mixing Matrix"). The way in which these conservation laws are violated is tested as follows:

a) $\Delta S = \Delta Q$ rule. In the semileptonic decay of strange particles, the strangeness change equals the change in charge of the hadrons. Tests come from limits on decay rates such as

$\Gamma(\Sigma^+ \to ne^+\nu)/\Gamma(\Sigma^+ \to \text{all}) < 5 \times 10^{-6}$, and from a detailed analysis of $K_L \to \pi e \nu$, which yields the parameter x, measured to be $(\text{Re}\,x, \text{Im}\,x) = (0.006 \pm 0.018, -0.003 \pm 0.026)$. Corresponding rules are $\Delta C = \Delta Q$ and $\Delta B = \Delta Q$.

b) Change of flavor by two units. In the Standard Model this occurs only in second-order weak interactions. The classic example is $\Delta S = 2$ via $K^0 - \overline{K}^0$ mixing, which is directly measured by $m(K_S) - m(K_L) = (3.489 \pm 0.009) \times 10^{-12}$ MeV. There is now evidence for $B^0 - \overline{B}^0$ mixing ($\Delta B = 2$), with the corresponding mass difference between the eigenstates $(m_{B^0_{\rm H}} - m_{B^0_{\rm L}}) = (0.723 \pm 0.032)\Gamma_{B^0} = (3.05 \pm 0.12) \times 10^{-10}$ MeV, and for B^0_s–$\overline{B}^0_s$ mixing, with $(m_{B^0_{sH}} - m_{B^0_{sL}}) > 14\Gamma_{B^0_s}$ or $> 6 \times 10^{-9}$ MeV (CL=95%). No evidence exists for $D^0 - \overline{D}^0$ mixing, which is expected to be much smaller in the Standard Model.

c) Flavor-changing neutral currents. In the Standard Model the neutral-current interactions do not change flavor. The low rate $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K_L \to \text{all}) = (7.2 \pm 0.5) \times 10^{-9}$ puts limits on such interactions; the nonzero value for this rate is attributed to a combination of the weak and electromagnetic interactions. The best test should come from $K^+ \to \pi^+\nu\overline{\nu}$, which occurs in the Standard Model only as a second-order weak process with a branching fraction of $(1 \text{ to } 8) \times 10^{-10}$. Observation of one event has been reported [4], yielding $\Gamma(K^+ \to \pi^+\nu\overline{\nu})/\Gamma(K^+ \to \text{all}) = (4.2^{+9.7}_{-3.5}) \times 10^{-10}$. Limits for charm-changing or bottom-changing neutral currents are much less stringent: $\Gamma(D^0 \to \mu^+\mu^-)/\Gamma(D^0 \to \text{all}) < 4 \times 10^{-6}$ and $\Gamma(B^0 \to \mu^+\mu^-)/\Gamma(B^0 \to \text{all}) < 7 \times 10^{-7}$. One cannot isolate flavor-changing neutral current (FCNC) effects in non leptonic decays. For example, the FCNC transition $s \to d + (\overline{u} + u)$ is equivalent to the charged-current transition $s \to u + (\overline{u} + d)$. Tests for FCNC are therefore limited to hadron decays into lepton pairs. Such decays are expected only in second-order in the electroweak coupling in the Standard Model.

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TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (*C*) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{\rm total}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		0.05 ± 0.06 (S = 1.5)
$\Gamma(\eta \to 3\gamma)/\Gamma_{\rm total}$		$<5 \times 10^{-4}$, CL = 95%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{\rm total}$	[*a*]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{\rm total}$	[*a*]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{\rm total}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{\rm total}$		$<3 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{\rm total}$	[*a*]	$<1.3 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{\rm total}$	[*a*]	$<1.1 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{\rm total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{\rm total}$	[*a*]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{\rm total}$	[*a*]	$<1.5 \times 10^{-5}$, CL = 90%

PARITY (*P*) INVARIANCE

e electric dipole moment	$(0.18 \pm 0.16) \times 10^{-26}$ *e*cm
μ electric dipole moment	$(3.7 \pm 3.4) \times 10^{-19}$ *e*cm
τ electric dipole moment (d_τ)	> -3.1 and $< 3.1 \times 10^{-16}$ *e*cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{\rm total}$	$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{\rm total}$	$<2 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{\rm total}$	$<9 \times 10^{-4}$, CL = 90%
p electric dipole moment	$(-4 \pm 6) \times 10^{-23}$ *e*cm
n electric dipole moment	$<0.97 \times 10^{-25}$ *e*cm, CL = 90%
Λ electric dipole moment	$<1.5 \times 10^{-16}$ *e*cm, CL = 95%

TIME REVERSAL (*T*) INVARIANCE

Limits on *e*, μ, τ, *p*, *n*, and Λ electric dipole moments under Parity Invariance above are also tests of Time Reversal Invariance.

μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		0.007 ± 0.023
α'/A		$(0 \pm 4) \times 10^{-3}$
β'/A		$(2 \pm 6) \times 10^{-3}$
τ electric dipole moment (d_τ)		> -3.1 and $< 3.1 \times 10^{-16}$ *e*cm, CL = 95%
Im(ξ) in $K^{\pm}_{\mu 3}$ decay (from transverse μ pol.)		-0.017 ± 0.025
Im(ξ) in $K^0_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$n \to pe^-\nu$ decay parameters		
ϕ_{AV}, phase of g_A relative to g_V	[*b*]	$(180.07 \pm 0.18)^\circ$
triple correlation coefficient *D*		$(-0.5 \pm 1.4) \times 10^{-3}$
triple correlation coefficient *D* for $\Sigma^- \to ne^-\overline{\nu}_e$		0.11 ± 0.10

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

Tests of Conservation Laws

CP INVARIANCE

$\mathrm{Re}(d^W_\tau)$		$<0.56 \times 10^{-17}$ ecm, CL = 95%
$\mathrm{Im}(d^W_\tau)$		$<1.5 \times 10^{-17}$ ecm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{\mathrm{total}}$		$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{\mathrm{total}}$		$<2 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{\mathrm{total}}$		$<9 \times 10^{-4}$, CL = 90%
$K^\pm \to \pi^\pm\pi^+\pi^-$ rate difference/average		$(0.07 \pm 0.12)\%$
$K^\pm \to \pi^\pm\pi^0\pi^0$ rate difference/average		$(0.0 \pm 0.6)\%$
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average		$(0.9 \pm 3.3)\%$
$(g_{\tau^+} - g_{\tau^-}) / (g_{\tau^+} + g_{\tau^-})$ for $K^\pm \to \pi^\pm\pi^+\pi^-$		$(-0.7 \pm 0.5)\%$
CP-violation parameters in K^0_S decay		
$\mathrm{Im}(\eta_{+-0}) = \mathrm{Im}(\mathrm{A}(K^0_S \to \pi^+\pi^-\pi^0,$ *CP*-violating$) / \mathrm{A}(K^0_L \to \pi^+\pi^-\pi^0))$		-0.002 ± 0.008
$\mathrm{Im}(\eta_{000})^2 = \Gamma(K^0_S \to 3\pi^0) / \Gamma(K^0_L \to 3\pi^0)$		<0.1, CL = 90%
charge asymmetry j for $K^0_L \to \pi^+\pi^-\pi^0$		0.0011 ± 0.0008
$\lvert\epsilon'_{+-\gamma}\rvert/\epsilon$ for $K^0_L \to \pi^+\pi^-\gamma$		<0.3, CL = 90%
$\Gamma(K^0_L \to \pi^0\mu^+\mu^-)/\Gamma_{\mathrm{total}}$	[*c*]	$<5.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to \pi^0 e^+ e^-)/\Gamma_{\mathrm{total}}$	[*c*]	$<4.3 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to \pi^0\nu\overline{\nu})/\Gamma_{\mathrm{total}}$	[*d*]	$<5.8 \times 10^{-5}$, CL = 90%
$A_{CP}(K^+K^-\pi^\pm)$ in $D^\pm \to K^+K^-\pi^\pm$		-0.017 ± 0.027
$A_{CP}(K^\pm K^{*0})$ in $D^+ \to K^+\overline{K}^{*0}$ and $D^- \to K^-K^{*0}$		-0.02 ± 0.05
$A_{CP}(\phi\pi^\pm)$ in $D^\pm \to \phi\pi^\pm$		-0.014 ± 0.033
$A_{CP}(\pi^+\pi^-\pi^\pm)$ in $D^\pm \to \pi^+\pi^-\pi^\pm$		-0.02 ± 0.04
$A_{CP}(K^+K^-)$ in $D^0, \overline{D}^0 \to K^+K^-$		0.026 ± 0.035
$A_{CP}(\pi^+\pi^-)$ in $D^0, \overline{D}^0 \to \pi^+\pi^-$		-0.05 ± 0.08
$A_{CP}(K^0_S\phi)$ in $D^0, \overline{D}^0 \to K^0_S\phi$		-0.03 ± 0.09
$A_{CP}(K^0_S\pi^0)$ in $D^0, \overline{D}^0 \to K^0_S\pi^0$		-0.018 ± 0.030
$\lvert\mathrm{Re}(\epsilon_{B^0})\rvert$		0.002 ± 0.008
$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})] / [\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$		-0.03 ± 0.06

CP VIOLATION OBSERVED

K^0_L branching ratios		
charge asymmetry in $K^0_{\ell 3}$ decays		
$\delta(\mu) = [\Gamma(\pi^-\mu^+\nu_\mu) - \Gamma(\pi^+\mu^-\overline{\nu}_\mu)]/\mathrm{sum}$		$(0.304 \pm 0.025)\%$
$\delta(e) = [\Gamma(\pi^-e^+\nu_e) - \Gamma(\pi^+e^-\overline{\nu}_e)]/\mathrm{sum}$		$(0.333 \pm 0.014)\%$
parameters for $K^0_L \to 2\pi$ decay		
$\lvert\eta_{00}\rvert = \lvert\mathrm{A}(K^0_L \to 2\pi^0) / \mathrm{A}(K^0_S \to 2\pi^0)\rvert$		$(2.275 \pm 0.019) \times 10^{-3}$ (S = 1.1)
$\lvert\eta_{+-}\rvert = \lvert\mathrm{A}(K^0_L \to \pi^+\pi^-) / \mathrm{A}(K^0_S \to \pi^+\pi^-)\rvert$		$(2.285 \pm 0.019) \times 10^{-3}$
$\epsilon'/\epsilon \approx \mathrm{Re}(\epsilon'/\epsilon) = (1 - \lvert\eta_{00}/\eta_{+-}\rvert)/3$	[*e*]	$(1.5 \pm 0.8) \times 10^{-3}$ (S = 1.8)
ϕ_{+-}, phase of η_{+-}		$(43.5 \pm 0.6)^\circ$
ϕ_{00}, phase of η_{00}		$(43.4 \pm 1.0)^\circ$
parameters for $K^0_L \to \pi^+\pi^-\gamma$ decay		
$\lvert\eta_{+-\gamma}\rvert = \lvert\mathrm{A}(K^0_L \to \pi^+\pi^-\gamma,$ *CP* violating$)/\mathrm{A}(K^0_S \to \pi^+\pi^-\gamma)\rvert$		$(2.35 \pm 0.07) \times 10^{-3}$
$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$		$(44 \pm 4)^\circ$
$\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{\mathrm{total}}$		$(2.067 \pm 0.035) \times 10^{-3}$ (S = 1.1)
$\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma_{\mathrm{total}}$		$(9.36 \pm 0.20) \times 10^{-4}$

CPT INVARIANCE

$(m_{W^+} - m_{W^-}) / m_{\mathrm{average}}$		-0.002 ± 0.007
$(m_{e^+} - m_{e^-}) / m_{\mathrm{average}}$		$<4 \times 10^{-8}$, CL = 90%
$\lvert q_{e^+} + q_{e^-}\rvert/e$		$<2 \times 10^{-18}$
$(g_{e^+} - g_{e^-}) / g_{\mathrm{average}}$		$(-0.5 \pm 2.1) \times 10^{-12}$
$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\mathrm{average}}$		$(2 \pm 8) \times 10^{-5}$
$(g_{\mu^+} - g_{\mu^-}) / g_{\mathrm{average}}$		$(-2.6 \pm 1.6) \times 10^{-8}$
$(m_{\pi^+} - m_{\pi^-}) / m_{\mathrm{average}}$		$(2 \pm 5) \times 10^{-4}$
$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\mathrm{average}}$		$(6 \pm 7) \times 10^{-4}$
$(m_{K^+} - m_{K^-}) / m_{\mathrm{average}}$		$(-0.6 \pm 1.8) \times 10^{-4}$
$(\tau_{K^+} - \tau_{K^-}) / \tau_{\mathrm{average}}$		$(0.11 \pm 0.09)\%$ (S = 1.2)
$K^\pm \to \mu^\pm\nu_\mu$ rate difference/average		$(-0.5 \pm 0.4)\%$
$K^\pm \to \pi^\pm\pi^0$ rate difference/average	[*f*]	$(0.8 \pm 1.2)\%$
$\lvert m_{K^0} - m_{\overline{K}^0}\rvert / m_{\mathrm{average}}$	[*g*]	$<10^{-18}$
phase difference $\phi_{00} - \phi_{+-}$		$(-0.1 \pm 0.8)^\circ$
CPT-violation parameters in K^0 decay		
real part of Δ		0.018 ± 0.020
imaginary part of Δ		0.02 ± 0.04
$(\lvert\frac{q_{\overline{p}}}{m_{\overline{p}}}\rvert - \frac{q_p}{m_p})/\lvert\frac{q}{m}\rvert_{\mathrm{average}}$		$(1.5 \pm 1.1) \times 10^{-9}$
$\lvert q_p + q_{\overline{p}}\rvert/e$		$<2 \times 10^{-5}$
$(\mu_p + \mu_{\overline{p}}) / \lvert\mu\rvert_{\mathrm{average}}$		$(-2.6 \pm 2.9) \times 10^{-3}$
$(m_n - m_{\overline{n}}) / m_{\mathrm{average}}$		$(9 \pm 5) \times 10^{-5}$
$(m_\Lambda - m_{\overline{\Lambda}}) / m_\Lambda$		$(-1.0 \pm 0.9) \times 10^{-5}$
$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_{\mathrm{average}}$		0.04 ± 0.09
$(\mu_{\Sigma^+} + \mu_{\overline{\Sigma}^-}) / \lvert\mu\rvert_{\mathrm{average}}$		0.014 ± 0.015
$(m_{\Xi^-} - m_{\overline{\Xi}^+}) / m_{\mathrm{average}}$		$(1.1 \pm 2.7) \times 10^{-4}$
$(\tau_{\Xi^-} - \tau_{\overline{\Xi}^+}) / \tau_{\mathrm{average}}$		0.02 ± 0.18
$(m_{\Omega^-} - m_{\overline{\Omega}^+}) / m_{\mathrm{average}}$		$(0 \pm 5) \times 10^{-4}$

TESTS OF NUMBER CONSERVATION LAWS

LEPTON FAMILY NUMBER

Lepton family number conservation means separate conservation of each of L_e, L_μ, L_τ.

$\Gamma(Z \to e^\pm\mu^\mp)/\Gamma_{\mathrm{total}}$	[*h*]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^\pm\tau^\mp)/\Gamma_{\mathrm{total}}$	[*h*]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^\pm\tau^\mp)/\Gamma_{\mathrm{total}}$	[*h*]	$<1.2 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^-\,{}^{32}\mathrm{S} \to e^-\,{}^{32}\mathrm{S}) / \sigma(\mu^-\,{}^{32}\mathrm{S} \to \nu_\mu\,{}^{32}\mathrm{P}^*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^-\,\mathrm{Ti} \to e^-\,\mathrm{Ti}) / \sigma(\mu^-\,\mathrm{Ti} \to \mathrm{capture})$		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^-\,\mathrm{Pb} \to e^-\,\mathrm{Pb}) / \sigma(\mu^-\,\mathrm{Pb} \to \mathrm{capture})$		$<4.6 \times 10^{-11}$, CL = 90%
limit on muonium → antimuonium conversion $R_g = G_C / G_F$		<0.018, CL = 90%
$\Gamma(\mu^- \to e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\mathrm{total}}$	[*i*]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^-\gamma)/\Gamma_{\mathrm{total}}$		$<4.9 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^-e^+e^-)/\Gamma_{\mathrm{total}}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^-2\gamma)/\Gamma_{\mathrm{total}}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^-\gamma)/\Gamma_{\mathrm{total}}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\gamma)/\Gamma_{\mathrm{total}}$		$<3.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\pi^0)/\Gamma_{\mathrm{total}}$		$<3.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\pi^0)/\Gamma_{\mathrm{total}}$		$<4.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-K^0)/\Gamma_{\mathrm{total}}$		$<1.3 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to \mu^-K^0)/\Gamma_{\mathrm{total}}$		$<1.0 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to e^-\eta)/\Gamma_{\mathrm{total}}$		$<8.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\eta)/\Gamma_{\mathrm{total}}$		$<9.6 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\rho^0)/\Gamma_{\mathrm{total}}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\rho^0)/\Gamma_{\mathrm{total}}$		$<6.3 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-K^*(892)^0)/\Gamma_{\mathrm{total}}$		$<5.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-K^*(892)^0)/\Gamma_{\mathrm{total}}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\overline{K}^*(892)^0)/\Gamma_{\mathrm{total}}$		$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\overline{K}^*(892)^0)/\Gamma_{\mathrm{total}}$		$<7.5 \times 10^{-6}$, CL = 90%

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

$\Gamma(\tau^- \to e^- \phi)/\Gamma_{\text{total}}$		$<6.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \phi)/\Gamma_{\text{total}}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- e^+ e^-)/\Gamma_{\text{total}}$		$<2.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \mu^+ \mu^-)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \mu^- \mu^-)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- e^+ e^-)/\Gamma_{\text{total}}$		$<1.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ e^- e^-)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \mu^+ \mu^-)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ \pi^-)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ \pi^-)/\Gamma_{\text{total}}$		$<8.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ K^-)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^- K^+)/\Gamma_{\text{total}}$		$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- K^+ K^-)/\Gamma_{\text{total}}$		$<6.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ K^-)/\Gamma_{\text{total}}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^- K^+)/\Gamma_{\text{total}}$		$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^+ K^-)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0 \pi^0)/\Gamma_{\text{total}}$		$<6.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0 \pi^0)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \eta\eta)/\Gamma_{\text{total}}$		$<3.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \eta\eta)/\Gamma_{\text{total}}$		$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0 \eta)/\Gamma_{\text{total}}$		$<2.4 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0 \eta)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^-$ light boson$)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-3}$, CL = 95%
$\Gamma(\tau^- \to \mu^-$ light boson$)/\Gamma_{\text{total}}$		$<5 \times 10^{-3}$, CL = 95%
ν oscillations. (For other lepton mixing effects in particle decays, see the Particle Listings.)		
$\overline{\nu}_e \not\to \overline{\nu}_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		$<9 \times 10^{-4}$ eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.02, CL = 90%
$\nu_e \to \nu_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.25, CL = 90%
$\overline{\nu}_e \to \overline{\nu}_\tau$		
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.7, CL = 90%
$\nu_\mu \to \nu_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.09 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<3.0 \times 10^{-3}$, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.14 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.004, CL = 95%
$\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.075 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<1.8 \times 10^{-3}$, CL = 90%
$\nu_\mu \to \nu_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.004, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<2.2 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<4.4 \times 10^{-2}$, CL = 90%
$\nu_\mu(\overline{\nu}_\mu) \to \nu_\tau(\overline{\nu}_\tau)$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<1.5 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<8 \times 10^{-3}$, CL = 90%
$\nu_e \not\to \nu_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.17 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<7 \times 10^{-2}$, CL = 90%
$\nu_\mu \not\to \nu_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.23 or >1500 eV^2
$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2	[j]	<0.02, CL = 90%
$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<7 or >1200 eV^2
$\sin^2(2\theta)$ for 190 eV^2 $<$ $\Delta(m^2)$ $<$ 320 eV^2	[k]	<0.02, CL = 90%
$\Gamma(\pi^+ \to \mu^+ \nu_e)/\Gamma_{\text{total}}$	[l]	$<8.0 \times 10^{-3}$, CL = 90%
$\Gamma(\pi^+ \to \mu^- e^+ e^+ \nu)/\Gamma_{\text{total}}$		$<1.6 \times 10^{-6}$, CL = 90%
$\Gamma(\pi^0 \to \mu^+ e^- + e^- \mu^+)/\Gamma_{\text{total}}$		$<1.72 \times 10^{-8}$, CL = 90%
$\Gamma(\eta \to \mu^+ e^- + \mu^- e^+)/\Gamma_{\text{total}}$		$<6 \times 10^{-6}$, CL = 90%
$\Gamma(K^+ \to \mu^- \nu e^+ e^+)/\Gamma_{\text{total}}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \nu_e)/\Gamma_{\text{total}}$	[l]	$<4 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \mu^+ e^-)/\Gamma_{\text{total}}$		$<2.1 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \mu^- e^+)/\Gamma_{\text{total}}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<3.3 \times 10^{-11}$, CL = 90%
$\Gamma(K^0_L \to e^\pm e^\pm \mu^\mp \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<6.1 \times 10^{-9}$, CL = 90%
$\Gamma(D^+ \to \pi^+ e^+ \mu^-)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to \pi^+ e^- \mu^+)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^+ e^+ \mu^-)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^+ e^- \mu^+)/\Gamma_{\text{total}}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \mu^\pm e^\mp)/\Gamma_{\text{total}}$	[h]	$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<8.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \eta e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<4.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \omega e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \phi e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<3.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{K}^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \overline{K}^*(892)^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \to \pi^+ e^+ \mu^-)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^+ e^- \mu^+)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^+ e^+ \mu^-)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^+ e^- \mu^+)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ \mu^+)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ \mu^+)/\Gamma_{\text{total}}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^0 \to e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to e^\pm \tau^\mp)/\Gamma_{\text{total}}$	[h]	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to \mu^\pm \tau^\mp)/\Gamma_{\text{total}}$	[h]	$<8.3 \times 10^{-4}$, CL = 90%
$\Gamma(B \to e^\pm \mu^\mp s)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-5}$, CL = 90%
$\Gamma(B^0_s \to e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[h]	$<4.1 \times 10^{-5}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}\text{S} \to e^+ {}^{32}\text{Si}^*)$ / $\sigma(\mu^- {}^{32}\text{S} \to \nu_\mu {}^{32}\text{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}\text{I} \to e^+ {}^{127}\text{Sb}^*)$ / $\sigma(\mu^- {}^{127}\text{I} \to$ anything$)$		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \text{Ti} \to e^+ \text{Ca})$ / $\sigma(\mu^- \text{Ti} \to$ capture$)$		$<8.9 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to \pi^- \gamma)/\Gamma_{\text{total}}$		$<2.8 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \pi^- \pi^0)/\Gamma_{\text{total}}$		$<3.7 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- \pi^-)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- \pi^-)/\Gamma_{\text{total}}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- K^-)/\Gamma_{\text{total}}$		$<2.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ K^- K^-)/\Gamma_{\text{total}}$		$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- K^-)/\Gamma_{\text{total}}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ K^- K^-)/\Gamma_{\text{total}}$		$<6.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \gamma)/\Gamma_{\text{total}}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0)/\Gamma_{\text{total}}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \eta)/\Gamma_{\text{total}}$		$<1.30 \times 10^{-3}$, CL = 90%
$\nu_e \to (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.14 eV^2, CL = 90%
$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.032, CL = 90%
$\nu_\mu \to (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.16 eV^2, CL = 90%
$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.001, CL = 90%
$\Gamma(\pi^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{\text{total}}$	[l]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ e^+)/\Gamma_{\text{total}}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \pi^- e^+ e^+)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$	[l]	$<1.5 \times 10^{-4}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{\text{total}}$	[l]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0 e^+ \overline{\nu}_e)/\Gamma_{\text{total}}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ e^+)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<8.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ \mu^+)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to \rho^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ e^+)/\Gamma_{\text{total}}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ \mu^+)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^+_s \to \pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<4.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+_s \to K^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^+_s \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma_{\text{total}}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma_{\text{total}}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- \mu^+ \mu^+)/\Gamma_{\text{total}}$		$<9.1 \times 10^{-3}$, CL = 90%

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

$\Gamma(\Xi^- \to p\mu^-\mu^-)/\Gamma_{\text{total}}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^-\mu^+\mu^+)/\Gamma_{\text{total}}$		$<7.0 \times 10^{-4}$, CL = 90%

BARYON NUMBER

$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{\text{total}}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{\text{total}}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{\text{total}}$		$<1.30 \times 10^{-3}$, CL = 90%
p mean life		$>1.6 \times 10^{25}$ years

A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.

$\tau(N \to e^+\pi)$		> 130 (n), > 550 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+\pi)$		> 100 (n), > 270 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+K)$		> 1.3 (n), > 150 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+K)$		> 1.1 (n), > 120 (p) $\times 10^{30}$ years, CL = 90%
limit on $n\overline{n}$ oscillations (bound n)	[m]	$>1.2 \times 10^8$ s, CL = 90%
limit on $n\overline{n}$ oscillations (free n)		$>0.86 \times 10^8$ s, CL = 90%

ELECTRIC CHARGE (Q)

e mean life / branching fraction	[n]	$>4.3 \times 10^{23}$ yr, CL = 68%
$\Gamma(n \to p\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$		$<8 \times 10^{-27}$, CL = 68%

$\Delta S = \Delta Q$ RULE

Allowed in second-order weak interactions.

$\Gamma(K^+ \to \pi^+\pi^+e^-\overline{\nu}_e)/\Gamma_{\text{total}}$		$<1.2 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \pi^+\pi^+\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$		$<3.0 \times 10^{-6}$, CL = 95%
$x = \text{A}(\overline{K}^0 \to \pi^-\ell^+\nu)/\text{A}(K^0 \to \pi^-\ell^+\nu) = \text{A}(\Delta S{=}-\Delta Q)/\text{A}(\Delta S{=}\Delta Q)$		
real part of x		0.006 ± 0.018 (S = 1.3)
imaginary part of x		-0.003 ± 0.026 (S = 1.2)
$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$		<0.043
$\Gamma(\Sigma^+ \to ne^+\nu_e)/\Gamma_{\text{total}}$		$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\Sigma^+ \to n\mu^+\nu_\mu)/\Gamma_{\text{total}}$		$<3.0 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^-e^+\nu_e)/\Gamma_{\text{total}}$		$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^-\mu^+\nu_\mu)/\Gamma_{\text{total}}$		$<9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ FORBIDDEN

Allowed in second-order weak interactions.

$\Gamma(\Xi^0 \to p\pi^-)/\Gamma_{\text{total}}$		$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to pe^-\overline{\nu}_e)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-3}$
$\Gamma(\Xi^0 \to p\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-3}$
$\Gamma(\Xi^- \to n\pi^-)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to ne^-\overline{\nu}_e)/\Gamma_{\text{total}}$		$<3.2 \times 10^{-3}$, CL = 90%
$\Gamma(\Xi^- \to n\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-2}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^-\pi^-)/\Gamma_{\text{total}}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^-e^-\overline{\nu}_e)/\Gamma_{\text{total}}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^-\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Omega^- \to \Lambda\pi^-)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$m_{K_L^0} - m_{K_S^0}$		$(0.5301 \pm 0.0014) \times 10^{10}\ \hbar\ \text{s}^{-1}$
$m_{K_L^0} - m_{K_S^0}$		$(3.489 \pm 0.009) \times 10^{-12}$ MeV

$\Delta C = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$\lvert m_{D_1^0} - m_{D_2^0}\rvert$	[o]	$<24 \times 10^{10}\ \hbar\ \text{s}^{-1}$, CL = 90%
$\lvert\Gamma_{D_1^0} - \Gamma_{D_2^0}\rvert/\Gamma_{D^0}$ mean life difference/average	[o]	<0.20, CL = 90%
$\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via } \overline{D}^0))/\Gamma(K^-\ell^+\nu_\ell)$		<0.005, CL = 90%
$\Gamma(K^+\pi^- \text{ or } K^+\pi^-\pi^+\pi^- (\text{via } \overline{D}^0))/\Gamma(K^-\pi^+ \text{ or } K^-\pi^+\pi^+\pi^-)$	[p]	< 0.0085 (or < 0.0037), CL = 90%
$\Gamma(D^0 \to K^+\ell^-\overline{\nu}_\ell(\text{via } \overline{D}^0))/\Gamma_{\text{total}}$		$<1.7 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^+\pi^- \text{ or } K^+\pi^-\pi^+\pi^- (\text{via } \overline{D}^0))/\Gamma_{\text{total}}$		$<1.0 \times 10^{-3}$, CL = 90%

$\Delta B = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

χ_d		0.172 ± 0.010
$\Delta m_{B^0} = m_{B_H^0} - m_{B_L^0}$		$(0.464 \pm 0.018) \times 10^{12}\ \hbar\ \text{s}^{-1}$
$x_d = \Delta m_{B^0}/\Gamma_{B^0}$		0.723 ± 0.032
χ_B at high energy		0.118 ± 0.006
$\Delta m_{B_s^0} = m_{B_{sH}^0} - m_{B_{sL}^0}$		$>9.1 \times 10^{12}\ \hbar\ \text{s}^{-1}$, CL = 95%
$x_s = \Delta m_{B_s^0}/\Gamma_{B_s^0}$		>14.0, CL = 95%
χ_s		>0.4975, CL = 95%

$\Delta S = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(K^+ \to \pi^+e^+e^-)/\Gamma_{\text{total}}$		$(2.74 \pm 0.23) \times 10^{-7}$
$\Gamma(K^+ \to \pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$		$(5.0 \pm 1.0) \times 10^{-8}$
$\Gamma(K^+ \to \pi^+\nu\overline{\nu})/\Gamma_{\text{total}}$		$(4.2^{+9.7}_{-3.5}) \times 10^{-10}$
$\Gamma(K_S^0 \to \mu^+\mu^-)/\Gamma_{\text{total}}$		$<3.2 \times 10^{-7}$, CL = 90%
$\Gamma(K_S^0 \to e^+e^-)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-7}$, CL = 90%
$\Gamma(K_S^0 \to \pi^0e^+e^-)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma_{\text{total}}$		$(7.2 \pm 0.5) \times 10^{-9}$ (S = 1.4)
$\Gamma(K_L^0 \to \mu^+\mu^-\gamma)/\Gamma_{\text{total}}$		$(3.25 \pm 0.28) \times 10^{-7}$
$\Gamma(K_L^0 \to e^+e^-)/\Gamma_{\text{total}}$		$<4.1 \times 10^{-11}$, CL = 90%
$\Gamma(K_L^0 \to e^+e^-\gamma)/\Gamma_{\text{total}}$		$(9.1 \pm 0.5) \times 10^{-6}$
$\Gamma(K_L^0 \to e^+e^-\gamma\gamma)/\Gamma_{\text{total}}$	[q]	$(6.5 \pm 1.2) \times 10^{-7}$
$\Gamma(K_L^0 \to \pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$	[q]	$<4.6 \times 10^{-7}$, CL = 90%
$\Gamma(K_L^0 \to \mu^+\mu^-e^+e^-)/\Gamma_{\text{total}}$		$(2.9^{+6.7}_{-2.4}) \times 10^{-9}$
$\Gamma(K_L^0 \to e^+e^-e^+e^-)/\Gamma_{\text{total}}$		$(4.1 \pm 0.8) \times 10^{-8}$ (S = 1.2)
$\Gamma(K_L^0 \to \pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$		$<5.1 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \to \pi^0e^+e^-)/\Gamma_{\text{total}}$		$<4.3 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \to \pi^0\nu\overline{\nu})/\Gamma_{\text{total}}$		$<5.8 \times 10^{-5}$, CL = 90%
$\Gamma(\Sigma^+ \to pe^+e^-)/\Gamma_{\text{total}}$		$<7 \times 10^{-6}$

$\Delta C = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(D^+ \to \pi^+e^+e^-)/\Gamma_{\text{total}}$	$<6.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<1.8 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \rho^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to e^+e^-)/\Gamma_{\text{total}}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \mu^+\mu^-)/\Gamma_{\text{total}}$	$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^0 \to \pi^0e^+e^-)/\Gamma_{\text{total}}$	$<4.5 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta e^+e^-)/\Gamma_{\text{total}}$	$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta\mu^+\mu^-)/\Gamma_{\text{total}}$	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0e^+e^-)/\Gamma_{\text{total}}$	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0\mu^+\mu^-)/\Gamma_{\text{total}}$	$<2.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega e^+e^-)/\Gamma_{\text{total}}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega\mu^+\mu^-)/\Gamma_{\text{total}}$	$<8.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \phi e^+e^-)/\Gamma_{\text{total}}$	$<5.2 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \phi\mu^+\mu^-)/\Gamma_{\text{total}}$	$<4.1 \times 10^{-4}$, CL = 90%

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

$\Gamma(D^0 \rightarrow \pi^+\pi^-\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$	$<8.1 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \rightarrow K^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \rightarrow K^*(892)^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\Lambda_c^+ \rightarrow p\mu^+\mu^-)/\Gamma_{\text{total}}$	$<3.4 \times 10^{-4}$, CL = 90%

$\Delta B = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(B^+ \rightarrow \pi^+e^+e^-)/\Gamma_{\text{total}}$	$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow \pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow K^+e^+e^-)/\Gamma_{\text{total}}$	$<6 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \rightarrow K^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \rightarrow K^*(892)^+e^+e^-)/\Gamma_{\text{total}}$	$<6.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \rightarrow K^*(892)^+\mu^+\mu^-)/\Gamma_{\text{total}}$	$<1.2 \times 10^{-3}$, CL = 90%
$\Gamma(B^0 \rightarrow \gamma\gamma)/\Gamma_{\text{total}}$	$<3.9 \times 10^{-5}$, CL = 90%
$\Gamma(B^0 \rightarrow e^+e^-)/\Gamma_{\text{total}}$	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \rightarrow \mu^+\mu^-)/\Gamma_{\text{total}}$	$<6.8 \times 10^{-7}$, CL = 90%
$\Gamma(B^0 \rightarrow K^0e^+e^-)/\Gamma_{\text{total}}$	$<3.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \rightarrow K^0\mu^+\mu^-)/\Gamma_{\text{total}}$	$<3.6 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \rightarrow K^*(892)^0e^+e^-)/\Gamma_{\text{total}}$	$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \rightarrow K^*(892)^0\mu^+\mu^-)/\Gamma_{\text{total}}$	$<2.3 \times 10^{-5}$, CL = 90%
$\Gamma(B^0 \rightarrow K^*(892)^0\nu\overline{\nu})/\Gamma_{\text{total}}$	$<1.0 \times 10^{-3}$, CL = 90%
$\Gamma(B \rightarrow e^+e^-s)/\Gamma_{\text{total}}$	$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(B \rightarrow \mu^+\mu^-s)/\Gamma_{\text{total}}$	$<5.8 \times 10^{-5}$, CL = 90%
$\Gamma(\overline{b} \rightarrow \mu^+\mu^-\text{anything})/\Gamma_{\text{total}}$	$<3.2 \times 10^{-4}$, CL = 90%
$\Gamma(B_s^0 \rightarrow \mu^+\mu^-)/\Gamma_{\text{total}}$	$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(B_s^0 \rightarrow e^+e^-)/\Gamma_{\text{total}}$	$<5.4 \times 10^{-5}$, CL = 90%
$\Gamma(B_s^0 \rightarrow \phi\nu\overline{\nu})/\Gamma_{\text{total}}$	$<5.4 \times 10^{-3}$, CL = 90%

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when $S > 1$, which often indicates that the measurements are inconsistent. When $S > 1.25$, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

[a] *C* parity forbids this to occur as a single-photon process.

[b] Time-reversal invariance requires this to be 0° or 180°.

[c] Allowed by higher-order electroweak interactions.

[d] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

[e] ϵ'/ϵ is derived from $|\eta_{00}/\eta_{+-}|$ measurements using theoretical input on phases.

[f] Neglecting photon channels. See, *e.g.*, A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).

[g] Derived from measured values of ϕ_{+-}, ϕ_{00}, $|\eta|$, $|m_{K_L^0} - m_{K_S^0}|$, and $\tau_{K_S^0}$, as described in the introduction to "Tests of Conservation Laws."

[h] The value is for the sum of the charge states of particle/antiparticle states indicated.

[i] A test of additive vs. multiplicative lepton family number conservation.

[j] $\Delta(m^2) = 100$ eV^2.

[k] 190 eV^2 $< \Delta(m^2) <$ 320 eV^2.

[l] Derived from an analysis of neutrino-oscillation experiments.

[m] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The second limit here is from reactor experiments with free neutrons.

[n] This is the best "electron disappearance" limit. The best limit for the mode $e^- \rightarrow \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

[o] The D_1^0-D_2^0 limits are inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via } \overline{D}^0))$ / $\Gamma(K^-\ell^+\nu_\ell)$.

[p] The larger limit (from E791) allows interference between the doubly Cabibbo-suppressed and mixing amplitudes; the smaller limit (from E691) doesn't. See the papers for details.

[q] See the K_L^0 Particle Listings for the energy limits used in this measurement.

REVIEWS, TABLES, AND PLOTS

Constants, Units, Atomic and Nuclear Properties

Standard Model and Related Topics

Astrophysics and Cosmology

Experimental Methods and Colliders

Mathematical Tools or Statistics, Monte Carlo, Group Theory

Kinematics, Cross-Section Formulae, and Plots

MAJOR REVIEWS IN THE PARTICLE LISTINGS

Gauge and Higgs bosons

Leptons

Quarks

Mesons

Baryons

Searches

Additional Reviews and Notes related to specific particles are located in the Particle Listings.

Table 1.1. Reviewed 1998 by B.N. Taylor (NIST). Based mainly on the "1986 Adjustment of the Fundamental Physical Constants" by E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding uncertainties in parts per million (ppm) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology).

Since the 1986 adjustment, new experiments have yielded improved values for a number of constants, including the Rydberg constant R_∞, the Planck constant h, the fine-structure constant α, and the molar gas constant R, and hence also for constants directly derived from these, such as the Boltzmann constant k and Stefan-Boltzmann constant σ. The new results and their impact on the 1986 recommended values are discussed extensively in "Recommended Values of the Fundamental Physical Constants: A Status Report," B.N. Taylor and E.R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95**, 497 (1990); see also E.R. Cohen and B.N. Taylor, "The Fundamental Physical Constants," Phys. Today, August 1997 Part 2, BG7. In general, the new results give uncertainties for the affected constants that are 5 to 7 times smaller than the 1986 uncertainties, but the changes in the values themselves are smaller than twice the 1986 uncertainties. Because the output values of a least-squares adjustment are correlated, the new results cannot readily be incorporated with the 1986 values. Until the next complete adjustment of the constants (expected by the end of 1998), the 1986 CODATA set, given (in part) below, remains the set of choice. The full 1986 set (to be replaced by the new set, when available) may be found at `http://physics.nist.gov/cuu`.

Quantity	Symbol, equation	Value	Uncert. (ppm)
speed of light in vacuum	c	299 792 458 m s^{-1}	exact[*]
Planck constant	h	6.626 075 5(40)$\times10^{-34}$ J s	0.60
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 572 66(63)$\times10^{-34}$ J s	0.60
		= 6.582 122 0(20)$\times10^{-22}$ MeV s	0.30
electron charge magnitude	e	1.602 177 33(49)$\times10^{-19}$ C = 4.803 206 8(15)$\times10^{-10}$ esu	0.30, 0.30
conversion constant	$\hbar c$	197.327 053(59) MeV fm	0.30
conversion constant	$(\hbar c)^2$	0.389 379 66(23) GeV^2 mbarn	0.59
electron mass	m_e	0.510 999 06(15) MeV/c^2 = 9.109 389 7(54)$\times10^{-31}$ kg	0.30, 0.59
proton mass	m_p	938.272 31(28) MeV/c^2 = 1.672 623 1(10)$\times10^{-27}$ kg	0.30, 0.59
		= 1.007 276 470(12) u = 1836.152 701(37) m_e	0.012, 0.020
deuteron mass	m_d	1875.613 39(57) MeV/c^2	0.30
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	931.494 32(28) MeV/c^2 = 1.660 540 2(10)$\times10^{-27}$ kg	0.30, 0.59
permittivity of free space	$\left.\begin{matrix}\epsilon_0\\ \mu_0\end{matrix}\right\}\ \epsilon_0\mu_0 = 1/c^2$	8.854 187 817 ... $\times10^{-12}$ F m^{-1}	exact
permeability of free space		$4\pi\times10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1/137.035 989 5(61)[†]	0.045
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 92(38)$\times10^{-15}$ m	0.13
electron Compton wavelength	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	3.861 593 23(35)$\times10^{-13}$ m	0.089
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	0.529 177 249(24)$\times10^{-10}$ m	0.045
wavelength of 1 eV/c particle	hc/e	1.239 842 44(37)$\times10^{-6}$ m	0.30
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 698 1(40) eV	0.30
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 246 16(18) barn	0.27
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 382 63(52)$\times10^{-11}$ MeV T^{-1}	0.089
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 66(28)$\times10^{-14}$ MeV T^{-1}	0.089
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	1.758 819 62(53)$\times10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	9.578 830 9(29)$\times10^{7}$ rad s^{-1} T^{-1}	0.30
gravitational constant[‡]	G_N	6.672 59(85)$\times10^{-11}$ m^3 kg^{-1} s^{-2}	128
		= 6.707 11(86)$\times10^{-39}$ $\hbar c$ (GeV/c^2)$^{-2}$	128
standard grav. accel., sea level	g	9.806 65 m s^{-2}	exact
Avogadro constant	N_A	6.022 136 7(36)$\times10^{23}$ mol^{-1}	0.59
Boltzmann constant	k	1.380 658(12)$\times10^{-23}$ J K^{-1}	8.5
		= 8.617 385(73)$\times10^{-5}$ eV K^{-1}	8.4
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(101 325 Pa)	22.414 10(19)$\times10^{-3}$ m^3 mol^{-1}	8.4
Wien displacement law constant	$b = \lambda_{\text{max}}T$	2.897 756(24)$\times10^{-3}$ m K	8.4
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	5.670 51(19)$\times10^{-8}$ W m^{-2} K^{-4}	34
Fermi coupling constant[**]	$G_F/(\hbar c)^3$	1.166 39(1)$\times10^{-5}$ GeV^{-2}	9
weak mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$)	0.23124(24)	1000
$W^\pm$ boson mass	m_W	80.41(10) GeV/c^2	1200
Z^0 boson mass	m_Z	91.187(7) GeV/c^2	77
strong coupling constant	$\alpha_s(m_Z)$	0.119(2)	17000

π = 3.141 592 653 589 793 238 e = 2.718 281 828 459 045 235 γ = 0.577 215 664 901 532 861

1 in ≡ 0.0254 m   1 G ≡ 10^{-4} T   1 eV = 1.602 177 33(49) × 10^{-19} J kT at 300 K = [38.681 49(33)]$^{-1}$ eV
1 Å ≡ 10^{-10} m   1 dyne ≡ 10^{-5} N   1 eV/c^2 = 1.782 662 70(54) × 10^{-36} kg   0 °C ≡ 273.15 K
1 barn ≡ 10^{-28} m^2 1 erg ≡ 10^{-7} J   2.997 924 58 × 10^9 esu = 1 C   1 atmosphere ≡ 760 torr ≡ 101 325 Pa

[*] The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

[†] At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is approximately 1/128.

[‡] Absolute lab measurements of G_N have been performed only on scales of $10^{-1\pm1}$ m.

[**] See discussion in Sec. 10 "Electroweak model and constraints on new physics."

2. ASTROPHYSICAL CONSTANTS

Table 2.1. Revised 1997 by D.E. Groom (LBNL) with the help of G.F. Smoot, M.S. Turner, and R.C. Willson. The figures in parentheses after some values give the one-standard deviation uncertainties in the last digit(s). While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

Quantity	Symbol, equation	Value	Reference
speed of light	c	$299\,792\,458$ m s^{-1}	defined Ref. [1]
Newtonian gravitational constant	G_N	$6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	Ref. [2]
astronomical unit	AU	$1.495\,978\,706\,6(2) \times 10^{11}$ m	Ref. [3,4]
tropical year (equinox to equinox) (1994)	yr	$31\,556\,925.2$ s	Ref. [3]
sidereal year (fixed star to fixed star) (1994)		$31\,558\,149.8$ s	Ref. [3]
mean sidereal day		$23^{\mathrm{h}}\,56^{\mathrm{m}}\,04^{\mathrm{s}}\!.090\,53$	Ref. [3]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.221\,047(79) \times 10^{19}$ GeV/c^2	uses Ref. [2]
		$= 2.176\,71(14) \times 10^{-8}$ kg	
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly	Ref. [5]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,08$ km	Ref. [6]
solar mass	$M_\odot$	$1.988\,92(25) \times 10^{30}$ kg	Ref. [7]
solar luminosity	$L_\odot$	$(3.846 \pm 0.008) \times 10^{26}$ W	Ref. [8]
solar equatorial radius	$R_\odot$	6.96×10^8 m	Ref. [3]
Earth equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m	Ref. [3]
Earth mass	$M_\oplus$	$5.973\,70(76) \times 10^{24}$ kg	Ref. [9]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_b}$ W	Ref. [10]
		(M_b = absolute bolometric magnitude	
		= bolometric magnitude at 10 pc)	
flux conversion	$\mathcal{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_b}$ W m^{-2}	from above
		(m_b = apparent bolometric magnitude)	
$v_\odot$ around center of Galaxy	$\Theta_\circ$	$220(20)$ km s^{-1}	Ref. [11]
solar distance from galactic center	$R_\circ$	$8.0(5)$ kpc	Ref. [12]
Hubble expansion rate†	H_0	$100\,h_0$ km s^{-1} Mpc^{-1}	
		$= h_0 \times (9.778\,13$ Gyr$)^{-1}$	Ref. [13]
normalized Hubble expansion rate†	h_0	$0.6 < h_0 < 0.8$	Ref. [14]
critical density of the universe†	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h_0^2\,M_\odot$Mpc^{-3}	
		$= 1.878\,82(24) \times 10^{-29}\,h_0^2$ g cm^{-3}	
		$= 1.053\,94(13) \times 10^{-5}\,h_0^2$ GeV cm^{-3}	
local disk density	ρ_{disk}	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	Ref. [15]
local halo density	ρ_{halo}	2–13 $\times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV/c^2cm^{-3}	Ref. [16]
pressureless matter density of the universe†	$\Omega_M \equiv \rho_M/\rho_c$	$0.2 < \Omega_M < 1$	Ref. [17]
scaled cosmological constant†	$\Omega_\Lambda = \Lambda c^2/3H_0^2$	$-1 < \Omega_\Lambda < 2$	Ref. [18]
scale factor for cosmological constant†	$c^2/3H_0^2$	$2.853 \times 10^{51}\,h_0^{-2}$ m^2	
age of the universe†	t_0	$11.5 + 1 \pm 1.5$ Gyr	Ref. [19]
	$\Omega_0 h_0^2$ for $\Lambda = 0$	≤ 2.4 for $t_0 \geq 10$ Gyr	Ref. [10]
		≤ 1 for $t_0 \geq 10$ Gyr, $h_0 > 0.4$	Ref. [10]
		≤ 0.4 for $t_0 \geq 10$ Gyr, $h_0 > 0.6$	Ref. [10]
cosmic background radiation (CBR) temperature†	T_0	2.728 ± 0.002 K	Ref. [20,21]
solar velocity with respect to CBR		369.3 ± 2.5 km s^{-1}	Ref. [21,22]
energy density of CBR	ρ_γ	$4.662\,3 \times 10^{-34}\,(T/2.728)^4$ g cm^{-3}	Ref. [10,21]
		$= 0.261\,53\,(T/2.728)^4$ eV cm^{-3}	
energy density of relativistic particles (CBR + ν)	ρ_R	$7.838\,8 \times 10^{-34}\,(T/2.728)^4$ g cm^{-3}	Ref. [10,21]
		$= 0.439\,72\,(T/2.728)^4$ eV cm^{-3}	
number density of CBR photons	n_γ	$411.87\,(T/2.728)^3$ cm^{-3}	Ref. [10,21]
entropy density/Boltzmann constant	s/k	$2\,899.3\,(T/2.728)^3$ cm^{-3}	Ref. [10]

† Subscript 0 indicates present-day values.

References:

1. B.W. Petley, Nature **303**, 373 (1983).
2. E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The set of constants resulting from this adjustment has been recommended for international use by CODATA (Committee on Data for Science and Technology).

   In the context of the scale dependence of field theoretic quantities, it should be remarked that absolute lab measurements of G_N have been performed only on scales of $10^{-1\pm1}$ m.
3. *The Astronomical Almanac for the year 1994*, U.S. Government Printing Office, Washington, and Her Majesty's Stationary Office, London (1993). Where possible, the values as adjusted for the fitting of the ephemerides to all the observational data are used.
4. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
5. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [4].
6. Heliocentric gravitational constant from Ref. 3 times $2/c^2$. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
7. Obtained from the heliocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation of G_N.
8. 1996 mean total solar irradiance (TSI) = 1367.5 ± 2.7 [23]; the solar luminosity is $4\pi \times (1\text{ AU})^2$ times this quantity. This value increased by 0.036% between the minima of solar cycles 21 and 22. It was modulated with an amplitude of 0.039% during solar cycle 21 [24].

   Sackmann *et al.* [25] use TSI = 1370 ± 2 W m^{-2}, but conclude that the solar luminosity ($L_\odot = 3.853 \times 10^{26}$ J s^{-1}) has an uncertainty of 1.5%. Their value is based on three 1977–83 papers, and they comment that the error is based on scatter among the reported values, which is substantially in excess of that expected from the individual quoted errors.

   The conclusion of the 1971 review by Thekaekara and Drummond [26] ($1353 \pm 1\%$ W m^{-2}) is often quoted [27]. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 27.

   Finally, a value based on the 1954 spectral curve due to Johnson [28] ($1395 \pm 1\%$ W m^{-2}, or $L_\odot = 3.92 \times 10^{26}$ J s^{-1}) has been used widely, and may be the basis for higher value of the solar luminosity and corresponding lower value of the solar absolute bolometric magnitude (4.72) still common in the literature [10].
9. Obtained from the geocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation of G_N.
10. E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley (1990).
11. F.J. Kerr and D. Lynden-Bell, Mon. Not. R. Astr. Soc. **221**, 1023–1038 (1985). "On the basis of this review these [$R_\circ = 8.5 \pm 1.1$ kpc and $\Theta_\circ = 220 \pm 20$ km s^{-1}] were adopted by resolution of IAU Commission 33 on 1985 November 21 at Delhi".
12. M.J. Reid, Annu. Rev. Astron. Astrophys. **31**, 345–372 (1993). Note that $\Theta_\circ$ from the 1985 IAU Commission 33 recommendations is adopted in this review, although the new value for $R_\circ$ is smaller.
13. Conversion using length of tropical year.
14. See the section on the Hubble Constant (Sec. 17 of this *Review*).
15. G. Gilmore, R.F.G. Wyse, and K. Kuijken, Annu. Rev. Astron. Astrophys. **27**, 555 (1989).
16. E.I. Gates, G. Gyuk, and M.S. Turner (Astrophys. J. **449**, L133 (1995)) find the local halo density to be $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}, but also comment that previously published estimates are in the range $1\text{–}10 \times 10^{-25}$ g cm^{-3}.

    The value 0.3 GeV/c^2 has been taken as "standard" in several papers setting limits on WIMP mass limits, *e.g.* in M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992).
17. As of April 1998 the concensus of observations seems to be $0.2 < \Omega_M < 0.5$, but systematic effects which raise the upper limit cannot be ruled out.
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    Work being reported as of April 1998 suggests a narrower range, possible excluding 0 in favor of a postive value.
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20. D.J. Fixsen *et al.*, Astrophy. J. **473**, 576 (1996). Error quoted here is one standard deviation.
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    K.R. Lang, *Astrophysical Data: Planets and Stars*, Springer-Verlag (1992).
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29. G.H. Jacoby *et al.*, J. Astron. Soc. Pacific **104**, 599–662 (1992).
30. J.P. Huchra, Science **256**, 321–325 (1992).

3. INTERNATIONAL SYSTEM OF UNITS (SI)

See "The International System of Units (SI)," NIST Special Publication **330**, B.N. Taylor, ed. (USGPO, Washington, DC, 1991); and "Guide for the Use of the International System of Units (SI)," NIST Special Publication **811**, 1995 edition, B.N. Taylor (USGPO, Washington, DC, 1995).

Physical quantity	Name of unit	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
Derived units with special names		
plane angle	radian	rad
solid angle	steradian	sr
frequency	hertz	Hz
energy	joule	J
force	newton	N
pressure	pascal	Pa
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T
luminous flux	lumen	lm
illuminance	lux	lx
celsius temperature	degree celsius	°C
activity (of a radioactive source)*	becquerel	Bq
absorbed dose (of ionizing radiation)*	gray	Gy
dose equivalent*	sievert	Sv

*See our section 26, on "Radioactivity and radiation protection," p. 163.

SI prefixes

10^{24}	yotta	(Y)
10^{21}	zetta	(Z)
10^{18}	exa	(E)
10^{15}	peta	(P)
10^{12}	tera	(T)
10^{9}	giga	(G)
10^{6}	mega	(M)
10^{3}	kilo	(k)
10^{2}	hecto	(h)
10	deca	(da)
10^{-1}	deci	(d)
10^{-2}	centi	(c)
10^{-3}	milli	(m)
10^{-6}	micro	(μ)
10^{-9}	nano	(n)
10^{-12}	pico	(p)
10^{-15}	femto	(f)
10^{-18}	atto	(a)
10^{-21}	zepto	(z)
10^{-24}	yocto	(y)

4. PERIODIC TABLE OF THE ELEMENTS

Table 4.1. Revised 1997 by C.G. Wohl (LBNL). The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. Atomic masses are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. However, although Th, Pa, and U have no stable isotopes, they do have characteristic terrestrial compositions, and meaningful weighted masses can be given. For elements 110–112, the atomic numbers of known isotopes are given. Adapted from the Commission of Atomic Weights and Isotopic Abundances, "Atomic Weights of the Elements 1995," Pure and Applied Chemistry **68**, 2339 (1996), and G. Audi and A.H. Wapstra, "The 1993 Mass Evaluation," Nucl. Phys. **A565**, 1 (1993). The names given below for elements 104 to 109 are those recommended by the International Union of Pure and Applied Chemistry in late 1997.

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha-nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

5. ELECTRONIC STRUCTURE OF THE ELEMENTS

Table 5.1. Reviewed 1998 by W.C. Martin (NIST). The electronic configurations and the ionization energies (except for a few newer values, marked with an *) are taken from "Atomic Spectroscopy," W.C. Martin and W.L. Wiese, in *Atomic, Molecular, and Optical Physics Reference Book*, G.W.F. Drake, ed., Amer. Inst. Phys., 1995. The electron configuration for, say, iron indicates an argon electronic core (see argon) plus six $3d$ electrons and two $4s$ electrons. The ionization energy is the least energy necessary to remove to infinity one electron from an atom of the element.

	Element		Electron configuration ($3d^5$ = five $3d$ electrons, *etc.*)		Ground state $^{2S+1}L_J$	Ionization energy (eV)
1	H	Hydrogen	$1s$		$^2S_{1/2}$	13.5984
2	He	Helium	$1s^2$		$^1S_0$	24.5874
3	Li	Lithium	(He)$2s$		$^2S_{1/2}$	5.3917
4	Be	Beryllium	(He)$2s^2$		$^1S_0$	9.3227
5	B	Boron	(He)$2s^2\ 2p$		$^2P_{1/2}$	8.2980
6	C	Carbon	(He)$2s^2\ 2p^2$		$^3P_0$	11.2603
7	N	Nitrogen	(He)$2s^2\ 2p^3$		$^4S_{3/2}$	14.5341
8	O	Oxygen	(He)$2s^2\ 2p^4$		$^3P_2$	13.6181
9	F	Fluorine	(He)$2s^2\ 2p^5$		$^2P_{3/2}$	17.4228
10	Ne	Neon	(He)$2s^2\ 2p^6$		$^1S_0$	21.5646
11	Na	Sodium	(Ne)$3s$		$^2S_{1/2}$	5.1391
12	Mg	Magnesium	(Ne)$3s^2$		$^1S_0$	7.6462
13	Al	Aluminum	(Ne)$3s^2\ 3p$		$^2P_{1/2}$	5.9858
14	Si	Silicon	(Ne)$3s^2\ 3p^2$		$^3P_0$	8.1517
15	P	Phosphorus	(Ne)$3s^2\ 3p^3$		$^4S_{3/2}$	10.4867
16	S	Sulfur	(Ne)$3s^2\ 3p^4$		$^3P_2$	10.3600
17	Cl	Chlorine	(Ne)$3s^2\ 3p^5$		$^2P_{3/2}$	12.9676
18	Ar	Argon	(Ne)$3s^2\ 3p^6$		$^1S_0$	15.7596
19	K	Potassium	(Ar) $4s$		$^2S_{1/2}$	4.3407
20	Ca	Calcium	(Ar) $4s^2$		$^1S_0$	6.1132
21	Sc	Scandium	(Ar)$3d\ 4s^2$	Transition elements	$^2D_{3/2}$	6.5615
22	Ti	Titanium	(Ar)$3d^2\ 4s^2$		$^3F_2$	6.8281
23	V	Vanadium	(Ar)$3d^3\ 4s^2$		$^4F_{3/2}$	6.7463
24	Cr	Chromium	(Ar)$3d^5\ 4s$		$^7S_3$	6.7665
25	Mn	Manganese	(Ar)$3d^5\ 4s^2$		$^6S_{5/2}$	7.4340
26	Fe	Iron	(Ar)$3d^6\ 4s^2$		$^5D_4$	7.9024
27	Co	Cobalt	(Ar)$3d^7\ 4s^2$		$^4F_{9/2}$	7.8810
28	Ni	Nickel	(Ar)$3d^8\ 4s^2$		$^3F_4$	7.6398
29	Cu	Copper	(Ar)$3d^{10}4s$		$^2S_{1/2}$	7.7264
30	Zn	Zinc	(Ar)$3d^{10}4s^2$		$^1S_0$	9.3942
31	Ga	Gallium	(Ar)$3d^{10}4s^2\ 4p$		$^2P_{1/2}$	5.9993
32	Ge	Germanium	(Ar)$3d^{10}4s^2\ 4p^2$		$^3P_0$	7.8994
33	As	Arsenic	(Ar)$3d^{10}4s^2\ 4p^3$		$^4S_{3/2}$	9.7886
34	Se	Selenium	(Ar)$3d^{10}4s^2\ 4p^4$		$^3P_2$	9.7524
35	Br	Bromine	(Ar)$3d^{10}4s^2\ 4p^5$		$^2P_{3/2}$	11.8138
36	Kr	Krypton	(Ar)$3d^{10}4s^2\ 4p^6$		$^1S_0$	13.9996
37	Rb	Rubidium	(Kr) $5s$		$^2S_{1/2}$	4.1771
38	Sr	Strontium	(Kr) $5s^2$		$^1S_0$	5.6949
39	Y	Yttrium	(Kr)$4d\ 5s^2$	Transition elements	$^2D_{3/2}$	6.2171
40	Zr	Zirconium	(Kr)$4d^2\ 5s^2$		$^3F_2$	6.6339
41	Nb	Niobium	(Kr)$4d^4\ 5s$		$^6D_{1/2}$	6.7589
42	Mo	Molybdenum	(Kr)$4d^5\ 5s$		$^7S_3$	7.0924
43	Tc	Technetium	(Kr)$4d^5\ 5s^2$		$^6S_{5/2}$	7.28
44	Ru	Ruthenium	(Kr)$4d^7\ 5s$		$^5F_5$	7.3605
45	Rh	Rhodium	(Kr)$4d^8\ 5s$		$^4F_{9/2}$	7.4589
46	Pd	Palladium	(Kr)$4d^{10}$		$^1S_0$	8.3369
47	Ag	Silver	(Kr)$4d^{10}5s$		$^2S_{1/2}$	7.5763
48	Cd	Cadmium	(Kr)$4d^{10}5s^2$		$^1S_0$	8.9938

49	In	Indium	$(\mathrm{Kr})4d^{10}5s^2\ 5p$		$^2P_{1/2}$	5.7864
50	Sn	Tin	$(\mathrm{Kr})4d^{10}5s^2\ 5p^2$		$^3P_0$	7.3439
51	Sb	Antimony	$(\mathrm{Kr})4d^{10}5s^2\ 5p^3$		$^4S_{3/2}$	8.6084
52	Te	Tellurium	$(\mathrm{Kr})4d^{10}5s^2\ 5p^4$		$^3P_2$	9.0096
53	I	Iodine	$(\mathrm{Kr})4d^{10}5s^2\ 5p^5$		$^2P_{3/2}$	10.4513
54	Xe	Xenon	$(\mathrm{Kr})4d^{10}5s^2\ 5p^6$		$^1S_0$	12.1298
55	Cs	Cesium	$(\mathrm{Xe})\ 6s$		$^2S_{1/2}$	3.8939
56	Ba	Barium	$(\mathrm{Xe})\ 6s^2$		$^1S_0$	5.2117
57	La	Lanthanum	$(\mathrm{Xe})\ 5d\ 6s^2$		$^2D_{3/2}$	5.5770
58	Ce	Cerium	$(\mathrm{Xe})4f\ 5d\ 6s^2$		$^1G_4$	5.5387
59	Pr	Praseodymium	$(\mathrm{Xe})4f^3\ 6s^2$	Lanthanides	$^4I_{9/2}$	5.464
60	Nd	Neodymium	$(\mathrm{Xe})4f^4\ 6s^2$		$^5I_4$	5.5250
61	Pm	Promethium	$(\mathrm{Xe})4f^5\ 6s^2$		$^6H_{5/2}$	5.58
62	Sm	Samarium	$(\mathrm{Xe})4f^6\ 6s^2$		$^7F_0$	5.6436
63	Eu	Europium	$(\mathrm{Xe})4f^7\ 6s^2$		$^8S_{7/2}$	5.6704
64	Gd	Gadolinium	$(\mathrm{Xe})4f^7\ 5d\ 6s^2$		$^9D_2$	6.1501
65	Tb	Terbium	$(\mathrm{Xe})4f^9\ 6s^2$		$^6H_{15/2}$	5.8638
66	Dy	Dysprosium	$(\mathrm{Xe})4f^{10}\ 6s^2$		$^5I_8$	5.9389
67	Ho	Holmium	$(\mathrm{Xe})4f^{11}\ 6s^2$		$^4I_{15/2}$	6.0215
68	Er	Erbium	$(\mathrm{Xe})4f^{12}\ 6s^2$		$^3H_6$	6.1077
69	Tm	Thulium	$(\mathrm{Xe})4f^{13}\ 6s^2$		$^2F_{7/2}$	6.1843
70	Yb	Ytterbium	$(\mathrm{Xe})4f^{14}\ 6s^2$		$^1S_0$	6.2542
71	Lu	Lutetium	$(\mathrm{Xe})4f^{14}5d\ 6s^2$		$^2D_{3/2}$	5.4259
72	Hf	Hafnium	$(\mathrm{Xe})4f^{14}5d^2\ 6s^2$	Transition elements	$^3F_2$	6.8251
73	Ta	Tantalum	$(\mathrm{Xe})4f^{14}5d^3\ 6s^2$		$^4F_{3/2}$	7.5496
74	W	Tungsten	$(\mathrm{Xe})4f^{14}5d^4\ 6s^2$		$^5D_0$	7.8640
75	Re	Rhenium	$(\mathrm{Xe})4f^{14}5d^5\ 6s^2$		$^6S_{5/2}$	7.8335
76	Os	Osmium	$(\mathrm{Xe})4f^{14}5d^6\ 6s^2$		$^5D_4$	8.4382*
77	Ir	Iridium	$(\mathrm{Xe})4f^{14}5d^7\ 6s^2$		$^4F_{9/2}$	8.9670*
78	Pt	Platinum	$(\mathrm{Xe})4f^{14}5d^9\ 6s$		$^3D_3$	8.9587
79	Au	Gold	$(\mathrm{Xe})4f^{14}5d^{10}6s$		$2S_{1/2}$	9.2255
80	Hg	Mercury	$(\mathrm{Xe})4f^{14}5d^{10}6s^2$		$^1S_0$	10.4375
81	Tl	Thallium	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p$		$^2P_{1/2}$	6.1082
82	Pb	Lead	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p^2$		$^3P_0$	7.4167
83	Bi	Bismuth	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p^3$		$^4S_{3/2}$	7.2856
84	Po	Polonium	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p^4$		$^3P_2$	8.4167
85	At	Astatine	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p^5$		$^2P_{3/2}$	
86	Rn	Radon	$(\mathrm{Xe})4f^{14}5d^{10}6s^2\ 6p^6$		$^1S_0$	10.7485
87	Fr	Francium	$(\mathrm{Rn})\ 7s$		$^2S_{1/2}$	4.0727
88	Ra	Radium	$(\mathrm{Rn})\ 7s^2$		$^1S_0$	5.2784
89	Ac	Actinium	$(\mathrm{Rn})\ 6d\ 7s^2$		$^2D_{3/2}$	5.17
90	Th	Thorium	$(\mathrm{Rn})\ 6d^2\ 7s^2$		$^3F_2$	6.3067
91	Pa	Protactinium	$(\mathrm{Rn})5f^2\ 6d\ 7s^2$	Actinides	$^4K_{11/2}$	5.89
92	U	Uranium	$(\mathrm{Rn})5f^3\ 6d\ 7s^2$		$^5L_6$	6.1941
93	Np	Neptunium	$(\mathrm{Rn})5f^4\ 6d\ 7s^2$		$^6L_{11/2}$	6.2657
94	Pu	Plutonium	$(\mathrm{Rn})5f^6\ 7s^2$		$^7F_0$	6.0262
95	Am	Americium	$(\mathrm{Rn})5f^7\ 7s^2$		$^8S_{7/2}$	5.9738
96	Cm	Curium	$(\mathrm{Rn})5f^7\ 6d\ 7s^2$		$^9D_2$	5.9915*
97	Bk	Berkelium	$(\mathrm{Rn})5f^9\ 7s^2$		$^6H_{15/2}$	6.1979*
98	Cf	Californium	$(\mathrm{Rn})5f^{10}\ 7s^2$		$^5I_8$	6.2817*
99	Es	Einsteinium	$(\mathrm{Rn})5f^{11}\ 7s^2$		$^4I_{15/2}$	6.42
100	Fm	Fermium	$(\mathrm{Rn})5f^{12}\ 7s^2$		$^3H_6$	6.50
101	Md	Mendelevium	$(\mathrm{Rn})5f^{13}\ 7s^2$		$^2F_{7/2}$	6.58
102	No	Nobelium	$(\mathrm{Rn})5f^{14}\ 7s^2$		$^1S_0$	6.65
103	Lr	Lawrencium	$(\mathrm{Rn})5f^{14}\ 7s^2\ 7p$?		$^2P_{1/2}$?	
104	Rf	Rutherfordium	$(\mathrm{Rn})5f^{14}6d^2\ 7s^2$?		$^3F_2$?	6.0?

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised April 1998 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2.

Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\vert_{\min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2	1	1.00794	1.00794	43.3	50.8	4.045 [e]	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [f]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.40	2.953[5.858]	165.0	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
Shielding concrete [g]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
Borosilicate glass (Pyrex) [h]			0.49707	66.2	97.6	1.695	28.3	12.7	2.23		1.474
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.70 [i]	27.05	12.3	2.20 [j]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [k]	184.5	(1.038) [k]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [l]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [m]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [n]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [o]			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) [p]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [q]			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator [r]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [s]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [t]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [u]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [v]			0.52019	64	92	1.83	29.83	≈150	0.1–0.3		1.0+0.25ρ
NEMA G10 plate [w]				62.6	90.2	1.87	33.0	19.4	1.7		—

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is ($\kappa$–1)×$10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)	—	—	—	—	—
He	(64)	—	—	—	—	—
Li	—	—	56	0.86	8.55(0°)	0.17
Be	—	37	12.4	0.436	5.885(0°)	0.38
C	—	0.7	0.6–4.3	0.165	1375(0°)	0.057
N_2	(548.5)	—	—	—	—	—
O_2	(495)	—	—	—	—	—
Ne	(127)	—	—	—	—	—
Al	—	10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8–7.3	0.162	—	0.20
Ar	(517)	—	—	—	—	—
Ti	—	16.8	8.5	0.126	50(0°)	—
Fe	—	28.5	11.7	0.11	9.71(20°)	0.18
Cu	—	16	16.5	0.092	1.67(20°)	0.94
Ge	16.0	—	5.75	0.073	—	0.14
Sn	—	6	20	0.052	11.5(20°)	0.16
Xe	—	—	—	—	—	—
W	—	50	4.4	0.032	5.5(20°)	0.48
Pt	—	21	8.9	0.032	9.83(0°)	0.17
Pb	—	2.6	29.3	0.038	20.65(20°)	0.083
U	—	—	36.1	0.028	29(20°)	0.064

1. R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984).
2. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **33**, 1189–1218 (1982).
3. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665–676 (1984).

a. σ_T, λ_T and λ_I are energy dependent. Values quoted apply to high energy range, where energy dependence is weak. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda^{-1} = N_A \sum w_j \sigma_j / A_j$, where N is Avogadro's number and w_j is the weight fraction of the jth element in the element, compound, or mixture. σ_{total} at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$. $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

b. For minimum-ionizing pions (results are very slightly different for other particles). Minimum dE/dx calculated in 1994, using density effect correction coefficients from Ref. 1. For electrons and positrons see Ref. 3. Ionization energy loss is discussed in Sec. 23.

c. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium are given. Corrections for molecular binding applied for H_2 and D_2. For atomic H, $X_0 = 63.05$ g/cm^2.

e. Density effect constants evaluated for $\rho = 0.0600$ g/cm^3 (H_2 bubble chamber?).

d. For molecular hydrogen (deuterium). For atomic H, $X_0 = 63.047$ g cm^{-2}.

f. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

g. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN-LRL-RHEL Shielding exp., UCRL-17841 (1968).

h. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

i. Calculated using Sternheimer's density effect parameterization for $\rho = 2.32$ g cm^{-3}. Actual value may be slightly lower.

j. For typical fused quartz. The specific gravity of crystalline quartz is 2.64.

k. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

l. Nylon, Type 6, $(NH(CH_2)_5CO)_n$

m. Polycarbonate (Lexan), $(C_{16}H_{14}O_3)_n$

n. Polyethylene terephthlate, monomer, $C_5H_4O_2$

o. Polyethylene, monomer $CH_2 = CH_2$

p. Polymide film (Kepton), $(C_{22}H_{10}N_2O_5)_n$

q. Polymethylmethacralate, monomer $CH_2 = C(CH_3)CO_2CH_3$

r. Polystyrene, monomer $C_6H_5CH{=}CH_2$

s. Teflon, monomer $CF_2 = CF_2$

t. Polyvinyltolulene, monomer 2-$CH_3C_6H_4CH{=}CH_2$

u. Bismuth germanate (BGO), $(Bi_2O_3)_2(GeO_2)_3$

v. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters, ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instrum. Methods **118**, 177 (1974).

w. G10-plate, typical 60% SiO_2 and 40% epoxy.

7. ELECTROMAGNETIC RELATIONS

Quantity	Gaussian CGS	SI
Conversion factors:		
Charge:	$2.997\,924\,58 \times 10^9$ esu	$= 1\ \mathrm{C} = 1\ \mathrm{A\ s}$
Potential:	$(1/299.792\,458)$ statvolt (ergs/esu)	$= 1\ \mathrm{V} = 1\ \mathrm{J\ C^{-1}}$
Magnetic field:	10^4 gauss $= 10^4$ dyne/esu	$= 1\ \mathrm{T} = 1\ \mathrm{N\ A^{-1} m^{-1}}$
Lorentz force:	$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$	$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
Maxwell equations:	$\nabla \cdot \mathbf{D} = 4\pi\rho$ $\nabla \times \mathbf{H} - \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} = \frac{4\pi}{c}\mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$	$\nabla \cdot \mathbf{D} = \rho$ $\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$
Constitutive relations:	$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}, \quad \mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$	$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P}, \quad \mathbf{H} = \mathbf{B}/\mu_0 - \mathbf{M}$
Linear media:	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$
Permitivity of free space:	1	$\epsilon_0 = 8.854\,187\ldots \times 10^{-12}\ \mathrm{F\ m^{-1}}$
Permeability of free space:	1	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N\ A^{-2}}$
Fields from potentials:	$\mathbf{E} = -\nabla V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$	$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$
Static potentials: (coulomb gauge)	$V = \sum_{\text{charges}} \frac{q_i}{r_i} = \int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{1}{c}\oint \frac{I\, d\boldsymbol{\ell}}{\lvert\mathbf{r} - \mathbf{r}'\rvert} = \frac{1}{c}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$	$V = \frac{1}{4\pi\epsilon_0} \sum_{\text{charges}} \frac{q_i}{r_i} = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{\mu_0}{4\pi}\oint \frac{I\, d\boldsymbol{\ell}}{\lvert\mathbf{r} - \mathbf{r}'\rvert} = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\, d^3x'$
Relativistic transformations: (**v** is the velocity of the primed frame as seen in the unprimed frame)	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \frac{1}{c}\mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c}\mathbf{v} \times \mathbf{E})$	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c^2}\mathbf{v} \times \mathbf{E})$

$$\frac{1}{4\pi\epsilon_0} = c^2 \times 10^{-7}\ \mathrm{N\ A^{-2}} = 8.987\,55\ldots \times 10^9\ \mathrm{m\ F^{-1}}\ ; \quad \frac{\mu_0}{4\pi} = 10^{-7}\ \mathrm{N\ A^{-2}}\ ; \quad c = \frac{1}{\sqrt{\mu_0\epsilon_0}} = 2.997\,924\ 58 \times 10^8\ \mathrm{m\ s^{-1}}$$

7.1. Impedances (SI units)

ρ = resistivity at room temperature in $10^{-8}\,\Omega$ m:
~ 1.7 for Cu
~ 2.4 for Au
~ 2.8 for Al
~ 5.5 for W
~ 73 for SS 304
~ 100 for Nichrome
(Al alloys may have double the Al value.)

For alternating currents, instantaneous current I, voltage V, angular frequency ω:

$$V = V_0\, e^{j\omega t} = ZI \, . \tag{7.1}$$

Impedance of self-inductance L: $Z = j\omega L$.

Impedance of capacitance C: $Z = 1/j\omega C$.

Impedance of free space: $Z = \sqrt{\mu_0/\epsilon_0} = 376.7\ \Omega$.

High-frequency surface impedance of a good conductor:

$$Z = \frac{(1+j)\,\rho}{\delta} \, , \quad \text{where } \delta = \text{skin depth} \, ; \tag{7.2}$$

$$\delta = \sqrt{\frac{\rho}{\pi\nu\mu}} \approx \frac{6.6\ \text{cm}}{\sqrt{\nu\,(\text{Hz})}} \quad \text{for Cu} \, . \tag{7.3}$$

7.2. Capacitance $\widehat{C}$ and inductance $\widehat{L}$ per unit length (SI units) [negligible skin depth]

Flat rectangular plates of width w, separated by $d \ll w$ with linear medium (ϵ, μ) between:

$$\widehat{C} = \epsilon\,\frac{w}{d} \, ; \qquad \widehat{L} = \mu\,\frac{d}{w} \, ; \tag{7.4}$$

$$\epsilon/\epsilon_0 = 2 \text{ to } 6 \text{ for plastics; } 4 \text{ to } 8 \text{ for porcelain, glasses;} \tag{7.5}$$

$$\mu/\mu_0 \simeq 1 \, . \tag{7.6}$$

Coaxial cable of inner radius r_1, outer radius r_2:

$$\widehat{C} = \frac{2\pi\,\epsilon}{\ln\,(r_2/r_1)} \, ; \qquad \widehat{L} = \frac{\mu}{2\pi}\,\ln\,(r_2/r_1) \, . \tag{7.7}$$

Transmission lines (no loss):

$$\text{Impedance: } Z = \sqrt{\widehat{L}/\widehat{C}} \, . \tag{7.8}$$

$$\text{Velocity: } v = 1/\sqrt{\widehat{L}\,\widehat{C}} = 1/\sqrt{\mu\epsilon} \, . \tag{7.9}$$

7.3. Synchrotron radiation (CGS units)

For a particle of charge e, velocity $v = \beta c$, and energy $E = \gamma mc^2$, traveling in a circular orbit of radius R, the classical energy loss per revolution δE is

$$\delta E = \frac{4\pi}{3}\,\frac{e^2}{R}\,\beta^3\,\gamma^4 \, . \tag{7.10}$$

For high-energy electrons or positrons ($\beta \approx 1$), this becomes

$$\delta E \ (\text{in MeV}) \approx 0.0885\ [E(\text{in GeV})]^4/R(\text{in m}) \, . \tag{7.11}$$

For $\gamma \gg 1$, the energy radiated per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9}\alpha\,\gamma\, F(\omega/\omega_c)\; d(\hbar\omega) \, , \tag{7.12}$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant and

$$\omega_c = \frac{3\gamma^3 c}{2R} \tag{7.13}$$

is the critical frequency. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\,y \int_y^\infty K_{5/3}\,(x)\ dx \, , \tag{7.14}$$

where $K_{5/3}\,(x)$ is a modified Bessel function of the third kind. For electrons or positrons,

$$\hbar\omega_c\,(\text{in keV}) \approx 2.22\ [E(\text{in GeV})]^3/R(\text{in m}) \, . \tag{7.15}$$

Fig. 7.1 shows $F(y)$ over the important range of y.

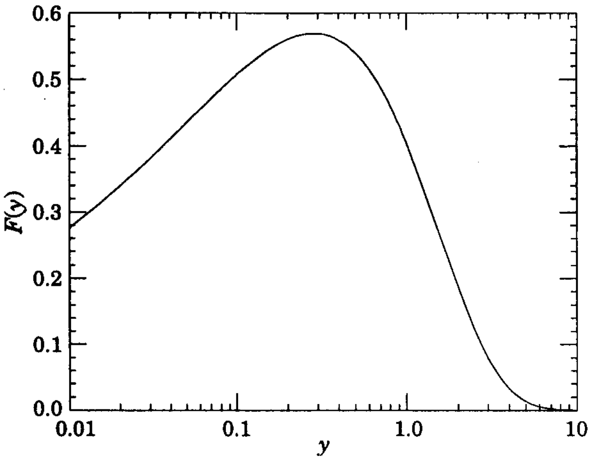

Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.

For $\gamma \gg 1$ and $\omega \ll \omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx 3.3\alpha\,(\omega R/c)^{1/3} \, , \tag{7.16}$$

whereas for

$$\gamma \gg 1 \text{ and } \omega \gtrsim 3\omega_c \, ,$$

$$\frac{dI}{d(\hbar\omega)} \approx \sqrt{\frac{3\pi}{2}}\,\alpha\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}\left[1+\frac{55}{72}\frac{\omega_c}{\omega}+\ldots\right] \, . \tag{7.17}$$

The radiation is confined to angles $\lesssim 1/\gamma$ relative to the instantaneous direction of motion. The mean number of photons emitted per revolution is

$$N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma \, , \tag{7.18}$$

and the mean energy per photon is

$$\langle\hbar\omega\rangle = \frac{8}{15\sqrt{3}}\hbar\omega_c \, . \tag{7.19}$$

When $\langle\hbar\omega\rangle \gtrsim O(E)$, quantum corrections are important.

See J.D. Jackson, *Classical Electrodynamics*, 2nd edition (John Wiley & Sons, New York, 1975) for more formulae and details. In his book, Jackson uses a definition of ω_c that is twice as large as the customary one given above.

8. NAMING SCHEME FOR HADRONS

Maintained 1996 by M. Roos (University of Finland) and C.G. Wohl (LBNL).

8.1. Introduction

We introduced in the 1986 edition [1] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of the light (u, d, and s) quarks. Old and new names were listed alongside until 1994. Names also change from edition to edition because some characteristic like mass or spin changes. The Summary Tables give both the new and old names whenever a change occurred.

8.2. "Neutral-flavor" mesons ($S=C=B=T=0$)

Table 8.1 shows the names for mesons having the strangeness and all heavy-flavor quantum numbers equal to zero. The scheme is designed for all ordinary non-exotic mesons, but it will work for many exotic types too, if needed.

Table 8.1: Symbols for mesons with the strangeness and all heavy-flavor quantum numbers equal to zero.

	$J^{PC}=$	0^{-+} 2^{-+} $\vdots$	1^{+-} 3^{+-} $\vdots$	1^{--} 2^{--} $\vdots$	0^{++} 1^{++} $\vdots$
$q\bar{q}$ content	$^{2S+1}L_J=$	$^1(L\,\text{even})_J$	$^1(L\,\text{odd})_J$	$^3(L\,\text{even})_J$	$^3(L\,\text{odd})_J$
$u\bar{d}, u\bar{u}-d\bar{d}, d\bar{u}$	$(I=1)$	π	b	ρ	a
$d\bar{d}+u\bar{u}$ and/or $s\bar{s}$	$(I=0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\bar{c}$		η_c	h_c	$\psi^{\dagger}$	χ_c
$b\bar{b}$		η_b	h_b	Υ	χ_b
$t\bar{t}$		η_t	h_t	θ	χ_t

†The J/ψ remains the J/ψ.

First, we assign names to those states with quantum numbers compatible with being $q\bar{q}$ states. The rows of the Table give the possible $q\bar{q}$ content. The columns give the possible parity/charge-conjugation states,

$$PC = -+,\ +-,\ --,\ \text{and}\ ++\ ;$$

these combinations correspond one-to-one with the angular-momentum state $^{2S+1}L_J$ of the $q\bar{q}$ system being

$$^1(L\ \text{even})_J,\ ^1(L\ \text{odd})_J,\ ^3(L\ \text{even})_J,\ \text{or}\ ^3(L\ \text{odd})_J\ .$$

Here S, L, and J are the spin, orbital, and total angular momenta of the $q\bar{q}$ system. The quantum numbers are related by

$$P = (-1)^{L+1},\ C = (-1)^{L+S},\ \text{and}\ G\ \text{parity}\ = (-1)^{L+S+I},$$

where of course the C quantum number is only relevant to neutral mesons.

The entries in the Table give the meson names. The spin J is added as a subscript except for pseudoscalar and vector mesons, and the mass is added in parentheses for mesons that decay strongly. However, for the lightest meson resonances, we omit the mass.

Measurements of the mass, quark content (where relevant), and quantum numbers I, J, P, and C (or G) of a meson thus fix its symbol. Conversely, these properties may be inferred unambiguously from the symbol.

If the main symbol cannot be assigned because the quantum numbers are unknown, X is used. Sometimes it is not known whether a meson is mainly the isospin-0 mix of $u\bar{u}$ and $d\bar{d}$ or is mainly $s\bar{s}$. A prime (or pair ω, ϕ) may be used to distinguish two such mixing states.

We follow custom and use spectroscopic names such as $\Upsilon(1S)$ as the primary name for most of those ψ, Υ, and χ states whose spectroscopic identity is known. We use the form $\Upsilon(9460)$ as an alternative, and as the primary name when the spectroscopic identity is not known.

Names are assigned for $t\bar{t}$ mesons, although the top quark is evidently so heavy that it is expected to decay too rapidly for bound states to form.

Gluonium states or other mesons that are not $q\bar{q}$ states are, if the quantum numbers are *not* exotic, to be named just as are the $q\bar{q}$ mesons. Such states will probably be difficult to distinguish from $q\bar{q}$ states and will likely mix with them, and we make no attempt to distinguish those "mostly gluonium" from those "mostly $q\bar{q}$."

An "exotic" meson with J^{PC} quantum numbers that a $q\bar{q}$ system cannot have, namely $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$, would use the same symbol as does an ordinary meson with all the same quantum numbers as the exotic meson except for the C parity. But then the J subscript may still distinguish it; for example, an isospin-0 1^{-+} meson could be denoted ω_1.

8.3. Mesons with nonzero S, C, B, and/or T

Since the strangeness or a heavy flavor of these mesons is nonzero, none of them are eigenstates of charge conjugation, and in each of them one of the quarks is heavier than the other. The rules are:

1. The main symbol is an upper-case italic letter indicating the heavier quark as follows:

   $$s \to \overline{K} \qquad c \to D \qquad b \to \overline{B} \qquad t \to T\ .$$

   We use the convention that *the flavor and the charge of a quark have the same sign.* Thus the strangeness of the s quark is negative, the charm of the c quark is positive, and the bottom of the b quark is negative. In addition, I_3 of the u and d quarks are positive and negative, respectively. The effect of this convention is as follows: *Any flavor carried by a charged meson has the same sign as its charge.* Thus the K^+, D^+, and B^+ have positive strangeness, charm, and bottom, respectively, and all have positive I_3. The D_s^+ has positive charm *and* strangeness. Furthermore, the $\Delta(\text{flavor}) = \Delta Q$ rule, best known for the kaons, applies to every flavor.
2. If the lighter quark is not a u or a d quark, its identity is given by a subscript. The D_s^+ is an example.
3. If the spin-parity is in the "normal" series, $J^P = 0^+, 1^-, 2^+, \cdots$, a superscript "*" is added.
4. The spin is added as a subscript except for pseudoscalar or vector mesons.

8.4. Baryons

The symbols N, Δ, Λ, Σ, Ξ, and Ω used for more than 30 years for the baryons made of light quarks (u, d, and s quarks) tell the isospin and quark content, and the same information is conveyed by the symbols used for the baryons containing one or more heavy quarks (c, b, and t quarks). The rules are:

1. Baryons with *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).
2. Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c, b, or t quark, its identity is given by a subscript.
3. Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, *etc.*
4. Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.

In short, the number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, *etc.*

Reference:

1. Particle Data Group: M. Aguilar-Benitez *et al.*, Phys. Lett. **170B** (1986).

9. QUANTUM CHROMODYNAMICS

9.1. The QCD Lagrangian

Revised September 1997 by I. Hinchliffe (LBNL).

Quantum Chromodynamics (QCD), the gauge field theory which describes the strong interactions of colored quarks and gluons, is one of the components of the SU(3)×SU(2)×U(1) Standard Model. A quark of specific flavor (such as a charm quark) comes in 3 colors; gluons come in eight colors; hadrons are color-singlet combinations of quarks, anti-quarks, and gluons. The Lagrangian describing the interactions of quarks and gluons is (up to gauge-fixing terms)

$$L_{\rm QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu}\, F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\, \gamma^\mu\, (D_\mu)_{ij}\, \psi^j_q - \sum_q m_q\, \overline{\psi}^i_q\, \psi_{qi}\ , \tag{9.1}$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\, A^a_\nu - \partial_\nu\, A^a_\mu + g_s\, f_{abc}\, A^b_\mu\, A^c_\nu\ , \tag{9.2}$$

$$(D_\mu)_{ij} = \delta_{ij}\, \partial_\mu - i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\ , \tag{9.3}$$

where g_s is the QCD coupling constant, and the f_{abc} are the structure constants of the SU(3) algebra (the λ matrices and values for f_{abc} can be found in "SU(3) Isoscalar Factors and Representation Matrices," Sec. 33 of this *Review*). The $\psi^i_q(x)$ are the 4-component Dirac spinors associated with each quark field of (3) color i and flavor q, and the $A^a_\mu(x)$ are the (8) Yang-Mills (gluon) fields. A complete list of the Feynman rules which derive from this Lagrangian, together with some useful color-algebra identities, can be found in Ref. 1.

The principle of "asymptotic freedom" (see below) determines that the renormalized QCD coupling is small only at high energies, and it is only in this domain that high-precision tests—similar to those in QED—can be performed using perturbation theory. Nonetheless, there has been in recent years much progress in understanding and quantifying the predictions of QCD in the nonperturbative domain, for example, in soft hadronic processes and on the lattice [2]. This short review will concentrate on QCD at short distances (large momentum transfers), where perturbation theory is the standard tool. It will discuss the processes that are used to determine the coupling constant of QCD. Other recent reviews of the coupling constant measurements may be consulted for a different perspective [3].

9.2. The QCD coupling and renormalization scheme

The renormalization scale dependence of the effective QCD coupling $\alpha_s = g_s^2/4\pi$ is controlled by the β-function:

$$\mu \frac{\partial \alpha_s}{\partial \mu} = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{4\pi^2}\alpha_s^3 - \frac{\beta_2}{64\pi^3}\alpha_s^4 - \cdots\ , \tag{9.4a}$$

$$\beta_0 = 11 - \frac{2}{3} n_f\ , \tag{9.4b}$$

$$\beta_1 = 51 - \frac{19}{3} n_f\ , \tag{9.4c}$$

$$\beta_2 = 2857 - \frac{5033}{9} n_f + \frac{325}{27} n_f^2\ ; \tag{9.4d}$$

where n_f is the number of quarks with mass less than the energy scale μ. The expression for the next term in this series (β_3) can be found in Ref. 4. In solving this differential equation for α_s, a constant of integration is introduced. This constant is the one fundamental constant of QCD that must be determined from experiment. The most sensible choice for this constant is the value of α_s at a fixed-reference scale μ_0, but it is more conventional to introduce the dimensional parameter Λ, since this provides a parametrization of the μ dependence of α_s. The definition of Λ is arbitrary. One way to define it (adopted here) is to write a solution of Eq. (9.4) as an expansion in inverse powers of $\ln(\mu^2)$:

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0\, \ln(\mu^2/\Lambda^2)} \left[1 - \frac{2\beta_1}{\beta_0^2}\, \frac{\ln\left[\ln(\mu^2/\Lambda^2)\right]}{\ln(\mu^2/\Lambda^2)} + \frac{4\beta_1^2}{\beta_0^4 \ln^2(\mu^2/\Lambda^2)} \times \left(\left(\ln\left[\ln(\mu^2/\Lambda^2)\right] - \frac{1}{2}\right)^2 + \frac{\beta_2\beta_0}{8\beta_1^2} - \frac{5}{4}\right)\right]\ . \tag{9.5a}$$

The last term in this expansion is

$$\mathcal{O}\left(\frac{\ln^2\left[\ln(\mu^2/\Lambda^2)\right]}{\ln^3(\mu^2/\Lambda^2)}\right)\ , \tag{9.5b}$$

and is usually neglected in the definition of Λ. We choose to include it. For a fixed value of $\alpha_s(M_Z)$, the inclusion of this term shifts the value of Λ by ~ 15 MeV. This solution illustrates the *asymptotic freedom* property: $\alpha_s \to 0$ as $\mu \to \infty$. Alternative definitions of Λ are possible. We adopt this as the standard. Values given by experiments using other definitions are adjusted as needed to meet our definition.

Consider a "typical" QCD cross section which, when calculated perturbatively, starts at $\mathcal{O}(\alpha_s)$:

$$\sigma = A_1\, \alpha_s + A_2\, \alpha_s^2 + \cdots\ . \tag{9.6}$$

The coefficients A_1, A_2 come from calculating the appropriate Feynman diagrams. In performing such calculations, various divergences arise, and these must be regulated in a consistent way. This requires a particular renormalization scheme (RS). The most commonly used one is the modified minimal subtraction ($\overline{\rm MS}$) scheme [5]. This involves continuing momentum integrals from 4 to 4–2ϵ dimensions, and then subtracting off the resulting $1/\epsilon$ poles and also ($\ln 4\pi - \gamma_E$), which is another artifact of continuing the dimension. (Here γ_E is the Euler-Mascheroni constant.) To preserve the dimensionless nature of the coupling, a mass scale μ must also be introduced: $g \to \mu^\epsilon g$. The finite coefficients A_i ($i > 2$) thus obtained depend implicitly on the renormalization convention used and explicitly on the scale μ.

The first two coefficients (β_0, β_1) in Eq. (9.4) are independent of the choice of RS's. In contrast, the coefficients of terms proportional to α_s^n for $n > 3$ *are* RS-dependent. The form given above for β_2 is in the $\overline{\rm MS}$ scheme. It has become conventional to use the $\overline{\rm MS}$ scheme for calculating QCD cross sections beyond leading order.

The fundamental theorem of RS dependence is straightforward. Physical quantities, in particular the cross section, calculated to all orders in perturbation theory, do not depend on the RS. It follows that a truncated series *does* exhibit RS dependence. In practice, QCD cross sections are known to leading order (LO), or to next-to-leading order (NLO), or in a few cases, to next-to-next-to-leading order (NNLO); and it is only the latter two cases, which have reduced RS dependence, that are useful for precision tests. At NLO the RS dependence is completely given by one condition which can be taken to be the value of the renormalization scale μ. At NNLO this is not sufficient, and μ is no longer equivalent to a choice of scheme; both must now be specified. One, therefore, has to address the question of what is the "best" choice for μ within a given scheme, usually $\overline{\rm MS}$. There is no definite answer to this question—higher-order corrections do not "fix" the scale, rather they render the theoretical predictions less sensitive to its variation.

One could imagine that choosing a scale μ characteristic of the typical energy scale (E) in the process would be most appropriate. In general, a poor choice of scale generates terms of order $\ln(E/\mu)$ in the A_i's. Various methods have been proposed including choosing: the scale for which the next-to-leading-order correction vanishes ("Fastest Apparent Convergence [6]"); the scale for which the next-to-leading-order prediction is stationary [7], (*i.e.*, the value of μ where $d\sigma/d\mu = 0$); or the scale dictated by the effective charge scheme [8] or by the BLM scheme [9]. By comparing the values of α_s that different reasonable schemes give, an estimate of theoretical errors can be obtained. It has also been suggested to replace the perturbation series by its Pade approximant [10]. Results obtained using this method have, in certain cases, a reduced scale dependence [11,12].

An important corollary is that if the higher-order corrections are naturally small, then the additional uncertainties introduced by the μ dependence are likely to be less than the experimental measurement errors. There are some processes, however, for which the choice of scheme *can* influence the extracted value of $\Lambda_{\overline{\rm MS}}$. There is no resolution to this problem other than to try to calculate even more terms in the perturbation series. It is important to note that, since the perturbation series is an asymptotic expansion, there is a limit to the precision with which any theoretical quantity can be calculated. In some processes, the highest-order perturbative terms may be comparable in size to nonperturbative corrections (sometimes called higher-twist or renormalon effects, for a discussion see [13]); an estimate of these terms and their uncertainties is required if a value of α_s is to be extracted.

In the cases where the higher-order corrections to a process are known and are large, some caution should be exercised when quoting the value of α_s. In what follows, we will attempt to indicate the size of the theoretical uncertainties on the extracted value of α_s. There are two simple ways to determine this error. First, we can estimate it by comparing the value of $\alpha_s(\mu)$ obtained by fitting data using the QCD formula to highest known order in α_s, and then comparing it with the value obtained using the next-to-highest-order formula (μ is chosen as the typical energy scale in the process). The corresponding Λ's are then obtained by evolving $\alpha_s(\mu)$ to $\mu = M_Z$ using Eq. (9.4) to the same order in α_s as the fit. Alternatively, we can vary the value of μ over a reasonable range, extracting a value of Λ for each choice of μ. This method is of its nature imprecise, since "reasonable" involves a subjective judgment. In either case, if the perturbation series is well behaved, the resulting error on $\alpha_s(M_Z)$ will be small.

In the above discussion we have ignored quark-mass effects, *i.e.*, we have assumed an idealized situation where quarks of mass greater than μ are neglected completely. In this picture, the β-function coefficients change by discrete amounts as flavor thresholds are crossed when integrating the differential equation for α_s. It follows that, for a relationship such as Eq. (9.5) to remain valid for all values of μ, Λ must also change as flavor thresholds are crossed. This leads to the concept of a different Λ for each range of μ corresponding to an effective number of massless quarks: $\Lambda \to \Lambda^{(n_f)}$. There is some arbitrariness in how this relationship is set up. As an idealized case, consider QCD with $n_f - 1$ massless quarks and one quark of mass M. Now imagine an experiment at energy scale μ; for example, this could be $e^+e^- \to$ hadrons at center-of-mass energy μ. If $\mu \gg M$, the mass M is negligible and the process is well described by QCD with n_f massless flavors and its parameter $\Lambda^{(n_f)}$ up to terms of order M^2/μ^2. Conversely if $\mu \ll M$, the heavy quark plays no role and the process is well described by QCD with $n_f - 1$ massless flavors and its parameter $\Lambda^{(n_f-1)}$ up to terms of order μ^2/M^2. If $\mu \sim M$, the effects of the quark mass are process-dependent and cannot be absorbed into the running coupling.

A mass scale μ' is chosen where the relationship between $\Lambda^{(n_f-1)}$ and $\Lambda^{(n_f)}$ will be fixed. μ' should be of order M and the relationship should not depend on it. A prescription has been given [14] which has this property. We use this procedure choosing $\mu' = M_Q$, where M_Q is the mass of the value of the running quark mass defined in the $\overline{\text{MS}}$ scheme (see the note on "Quark Masses" in the Particle Listings for more details), *i.e.*, where $M_{\overline{\text{MS}}}(M_Q) = M_Q$. Then [14]

$$\begin{aligned}
{\beta_0}^{n_f-1} \ln\left(\frac{\Lambda^{(n_f)}}{\Lambda^{(n_f-1)}}\right)^2 &= ({\beta_0}^{n_f} - {\beta_0}^{n_f-1})\ \ln\left(\frac{M_Q}{\Lambda^{(n_f)}}^2\right) \\
&+ 2\left(\frac{{\beta_1}^{n_f}}{{\beta_0}^{n_f}} - \frac{{\beta_1}^{n_f-1}}{{\beta_0}^{n_f-1}}\right)\ \ln\left[\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2\right] \\
&- \frac{2{\beta_1}^{n_f-1}}{{\beta_0}^{n_f-1}}\ \ln\left(\frac{{\beta_0}^{n_f}}{{\beta_0}^{n_f-1}}\right) \\
&+ \frac{4\frac{{\beta_1}^{n_f}}{({\beta_0}^{n_f})^2}\left(\frac{{\beta_1}^{n_f}}{{\beta_0}^{n_f}} - \frac{{\beta_1}^{n_f-1}}{{\beta_0}^{n_f-1}}\right)\ \ln\left[\ln\left(\frac{M_Q}{\Lambda^{n_f}}\right)^2\right]}{\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2} \\
&+ \frac{\frac{1}{{\beta_0}^{n_f}}\left[\left(\frac{2{\beta_1}^{n_f}}{{\beta_0}^{n_f}}\right)^2 - \left(\frac{2{\beta_1}^{n_f-1}}{{\beta_0}^{n_f-1}}\right)^2 - \frac{{\beta_2}^{n_f}}{2{\beta_0}^{n_f}} + \frac{{\beta_2}^{n_f-1}}{2{\beta_0}^{n_f-1}} - \frac{22}{9}\right]}{\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2} \;.
\end{aligned} \tag{9.7}$$

This result is valid to order α_s^3 (or alternatively to terms of order $1/\ln^2[(M_Q/\Lambda^{(n_f)})^2]$). The order α_s^4 expression is also available [15].

An alternative matching procedure can be used [16]. This procedure requires the equality $\alpha_s(\mu)^{(n_f)} = \alpha_s(\mu)^{(n_f-1)}$ for $\mu = M_Q$. This matching is somewhat arbitrary; a different relation between $\Lambda^{(n_f)}$ and $\Lambda^{(n_f-1)}$ would result if $\mu = M_Q/2$ were used. In practice, the differences between these procedures are very small. $\Lambda^{(5)} = 200$ MeV corresponds to $\Lambda^{(4)} = 289$ MeV in the scheme of Ref. 16 and $\Lambda^{(4)} = 280$ MeV in the scheme adopted above. Note that the differences between $\Lambda^{(5)}$ and $\Lambda^{(4)}$ are numerically very significant.

Data from deep-inelastic scattering are in a range of energy where the bottom quark is not readily excited, and hence, these experiments quote $\Lambda^{(4)}_{\overline{\text{MS}}}$. Most data from PEP, PETRA, TRISTAN, LEP, and SLC quote a value of $\Lambda^{(5)}_{\overline{\text{MS}}}$ since these data are in an energy range where the bottom quark is light compared to the available energy. We have converted it to $\Lambda^{(4)}_{\overline{\text{MS}}}$ as required. A few measurements, including the lattice gauge theory values from the ψ system and from τ decay are at sufficiently low energy that $\Lambda^{(3)}_{\overline{\text{MS}}}$ is appropriate.

In order to compare the values of α_s from various experiments, they must be evolved using the renormalization group to a common scale. For convenience, this is taken to be the mass of the Z boson. This evolution uses third-order perturbation theory and can introduce additional errors particularly if extrapolation from very small scales is used. The variation in the charm and bottom quark masses ($m_b = 4.3 \pm 0.2$ and $m_c = 1.3 \pm 0.3$ are used) can also introduce errors. These result in a fixed value of $\alpha_s(2$ GeV) giving an uncertainty in $\alpha_s(M_Z) = \pm 0.001$ if only perturbative evolution is used. There could be additional errors from nonperturbative effects that enter at low energy. All values are in the $\overline{\text{MS}}$ scheme unless otherwise noted.

9.3. QCD in deep-inelastic scattering

The original and still one of the most powerful quantitative tests of perturbative QCD is the breaking of Bjorken scaling in deep-inelastic lepton-hadron scattering. In the leading-logarithm approximation, the measured structure functions $F_i(x, Q^2)$ are related to the quark distribution functions $q_i(x, Q^2)$ according to the naive parton model, by the formulae in "Cross-section Formulae for Specific Processes," Sec. 36 of this *Review*. (In that section, q_i is denoted by the notation f_q). In describing the way in which scaling is broken in QCD, it is convenient to define nonsinglet and singlet quark distributions:

$$F^{NS} = q_i - q_j \qquad F^S = \sum_i (q_i + \overline{q}_i) \;. \tag{9.8}$$

The nonsinglet structure functions have nonzero values of flavor quantum numbers such as isospin or baryon number. The variation with Q^2 of these is described by the so-called DGLAP equations [17,18]:

$$Q^2 \frac{\partial F^{NS}}{\partial Q^2} = \frac{\alpha_s(|Q|)}{2\pi} P^{qq} * F^{NS} \tag{9.9a}$$

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} F^S \\ G \end{pmatrix} = \frac{\alpha_s(|Q|)}{2\pi} \begin{pmatrix} P^{qq} & 2n_f P^{qg} \\ P^{gq} & P^{gg} \end{pmatrix} * \begin{pmatrix} F^S \\ G \end{pmatrix} \tag{9.9b}$$

where $*$ denotes a convolution integral:

$$f * g = \int_x^1 \frac{dy}{y}\, f(y)\, g\left(\frac{x}{y}\right) \;. \tag{9.10}$$

The leading-order Altarelli-Parisi [18] splitting functions are

$$P^{qq} = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+}\right] + 2\delta(1-x) \;, \tag{9.11a}$$

$$P^{qg} = \frac{1}{2}\left[x^2 + (1-x)^2\right] \;, \tag{9.11b}$$

$$P^{gq} = \frac{4}{3}\left[\frac{1+(1-x)^2}{x}\right] \;, \tag{9.11c}$$

$$P^{gg} = 6\left[\frac{1-x}{x} + x(1-x) + \frac{x}{(1-x)_+} + \frac{11}{12}\delta(1-x)\right] - \frac{n_f}{3}\delta(1-x) \;. \tag{9.11d}$$

Here the gluon distribution $G(x,Q^2)$ has been introduced and $1/(1-x)_+$ means

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^1 dx \, \frac{f(x)-f(1)}{(1-x)} \;. \tag{9.12}$$

The precision of contemporary experimental data demands that higher-order corrections also be included [19]. The above results are for massless quarks. At low Q^2 values, there are also important "higher-twist" (HT) contributions of the form:

$$F_i(x,Q^2) = F_i^{(LT)}\,(x,Q^2) + \frac{F_i^{(HT)}(x,Q^2)}{Q^2} + \cdots \;. \tag{9.13}$$

Leading twist (LT) indicates a term whose behavior is predicted by perturbative QCD. These corrections are numerically important only for $Q^2 < \mathcal{O}(\text{few GeV}^2)$ except for x very close to 1. At very large values of x corrections proportional to $\log(1-x)$ can become important [20].

A detailed review of the current status of the experimental data can be found, for example, in Refs. [21–23], and only a brief summary will be presented here. We shall only include determinations of Λ from the recently published results; the earlier editions of this *Review* should be consulted for the earlier data. In any event, the recent results will dominate the average since their errors are smaller. Data now exist from HERA at much smaller values of x than the fixed-target data. They provide valuable information about the shape of the antiquark and gluon distribution functions at $x \sim 10^{-4}$ [24].

From Eq. (9.9), it is clear that a nonsinglet structure function offers in principle the most precise test of the theory, since the Q^2 evolution is independent of the unmeasured gluon distribution. The CCFR collaboration fit to the Gross-Llewellyn Smith sum rule [25] is known to order α_s^3 [26]

$$\int_0^1 dx \left(F_3^{\overline{\nu}p}(x,Q^2) + F_3^{\nu p}(x,Q^2)\right) = 3\left[\left(1 - \frac{\alpha_s}{\pi}(1 + 3.58\frac{\alpha_s}{\pi} + 19.0(\frac{\alpha_s}{\pi})^2\right) - \Delta HT\right] \;, \tag{9.14}$$

where the higher-twist contribution $\Delta HT = (0.09 \pm 0.045)/Q^2$ [26,27]. Using the CCFR data [28], this gives α_s (1.76 GeV) = 0.26 ± 0.035 (expt.) ± 0.03 (theory). The error from higher-twist terms dominates the theoretical error, the higher-twist term being approximately 50% larger than the α_s^3 term. The CCFR data have been recalibrated since this result was published [29] so this result can be expected to change; it should not therefore be included in an average. An experiment at Serpukov [30] has measured the sum rule at $< Q^2 >= 1.7$ GeV^2 and obtains α_s (1.7 GeV) = 0.35 ± 0.03 (expt.) or $\Lambda^{(4)}_{\overline{\rm MS}} = 359 \pm 59$(expt.) MeV. The error does not include (theoretical) errors arising from the choice of μ and the higher-twist terms. Estimating the uncertainty from the higher-twist terms as 50% of their effect gives ±60 MeV of additional error in the extracted value of $\Lambda^{(4)}_{\overline{\rm MS}}$.

Measurements involving singlet-dominated structure functions, such as F_2, result in correlated measurements of $\Lambda^{(4)}_{\overline{\rm MS}}$ and the gluon distribution. By utilizing high-statistics data at large x (> 0.25) and large Q^2, where F_2 behaves like an nonsinglet and F_3 at smaller x, a nonsinglet fit can be performed with better statistical precision, and hence, the error on the measured value of $\Lambda^{(4)}_{\overline{\rm MS}}$ is much reduced. Recently, CCFR gives $\Lambda^{(4)}_{\overline{\rm MS}} = 337 \pm 28 \pm 13$(higher-twist) MeV [29] from $F_2(\nu N)$ and $F_3(\nu N)$. There is an additional uncertainty of ±59 MeV from the choice of scale. The NMC collaboration [31] gives $\alpha_s(7\text{ GeV}^2) = 0.264 \pm 0.018(\text{stat.}) \pm 0.070(\text{syst.}) \pm 0.013(\text{ higher-twist})$. The systematic error is larger than the CCFR result, partially because the data are at smaller values of x and the gluon distribution is more important. A reanalysis [32] of EMC data [33] gives $\Lambda^{(4)}_{\overline{\rm MS}} = 211 \pm 80 \pm 80$ MeV from $F_2(\nu N)$. Finally a combined analysis [34] of SLAC [35] and BCDMS [36] data gives $\Lambda^{(4)}_{\overline{\rm MS}} = 263 \pm 42 \pm 55$ MeV. Here the systematic error is an estimate of the uncertainty due to the choice of Q^2 used in the argument of α_s, and in the scale at which the structure functions (factorization scale) used in the QCD calculation are evaluated.

The results from Refs. [29–32], [34], and [37] can be combined to give $\Lambda^{(4)}_{\overline{\rm MS}} = 305 \pm 25 \pm 50$ MeV which corresponds to $\alpha_s(M_Z) = 0.117 \pm 0.002 \pm 0.004$, Here the first error is a combination of statistical and systematic errors, and the second error is due to the scale uncertainty. This result is an average of the results weighted by their statistical and systematic errors. The scale error, which is common to all, is then reapplied to the average.

The spin-dependent structure functions, measured in polarized lepton nucleon scattering, can also be used to determine α_s. Here the values of $Q^2 \sim 2.5$ GeV^2 are small and higher-twist corrections are important. A fit [38] using the measured spin dependent structure functions themselves [39] gives $\alpha_s(M_Z) = 0.120^{+0.004}_{-0.005}(\text{expt.})^{+0.009}_{-0.006}(\text{theory})$. These authors also determine α_s from the Bjorken sum rule [40] and obtain $\alpha_s(M_Z) = 0.118^{+0.010}_{-0.024}$; consistent with an earlier determination [41], the larger error being due to the extrapolation into the (unmeasured) small x region. Theoretically, the sum rule is preferable as the perturbative QCD result is known to higher order and these terms are important at the low Q^2 involved. It has been shown that the theoretical errors associated with the choice of scale are considerably reduced by the use of Pade approximants [11] which results in $\alpha_s(1.7\text{ GeV}) = 0.328 \pm 0.03(\text{expt.}) \pm 0.025(\text{theory})$ corresponding to $\alpha_s(M_Z) = 0.116^{+0.003}_{-0.005}(\text{expt.}) \pm 0.003(\text{theory})$. No error is included from the extrapolation into the region of x that is unmeasured. If data were to become available at smaller values of x so that this extrapolation could be more tightly constrained, the sum rule method would provide the best determination of α_s; the more conservative result from the structure functions themselves is used in the average.

At very small values of x and Q^2, the x and Q^2 dependence of the structure functions is predicted by perturbative QCD [42]. Here terms to all orders in $\alpha_s \ln(1/x)$ are summed. The data from HERA [24] on $F_2^{ep}(x,Q^2)$ can be fitted to this form [43], including the NLO terms which are required to fix the Q^2 scale. The data are dominated by 4 GeV^2 < Q^2 < 100 GeV^2. The fit [45] using H1 data [46] gives $\alpha_s(M_Z) = 0.122 \pm 0.004$ (expt.) ± 0.009 (theory). (The theoretical error is taken from Ref. 43.) The dominant part of the theoretical error is from the scale dependence; errors from terms that are suppressed by $1/\log(1/x)$ in the quark sector are included [44] while those from the gluon sector are not.

Typically, Λ is extracted from the deep inelastic scattering data by parameterizing the parton densities in a simple analytic way at some Q_0^2, evolving to higher Q^2 using the next-to-leading-order evolution equations, and fitting globally to the measured structure functions to obtain $\Lambda^{(4)}_{\overline{\rm MS}}$. Thus, an important by-product of such studies is the extraction of parton densities at a fixed-reference value of Q_0^2. These can then be evolved in Q^2 and used as input for phenomenological studies in hadron-hadron collisions (see below). To avoid having to evolve from the starting Q_0^2 value each time, a parton density is required; it is useful to have available a simple analytic approximation to the densities valid over a range of x and Q^2 values. A package is available from the CERN computer library that includes an exhaustive set of fits [47]. Most of these fits are obsolete. In using a parameterization to predict event rates, a next-to-leading order fit must be used if the process being calculated is known to next-to-leading order in QCD perturbation theory. In such a case, there is an additional scheme dependence; this scheme dependence is reflected in the $\mathcal{O}(\alpha_s)$ corrections that appear in the relations between the structure functions and the quark distribution functions. There are two common schemes: a deep-inelastic scheme where there are no order α_s corrections in the formula for $F_2(x,Q^2)$ and the minimal subtraction scheme. It is important when these next-to-leading order fits are used in other processes (see below), that the same scheme is used in the calculation of the partonic rates.

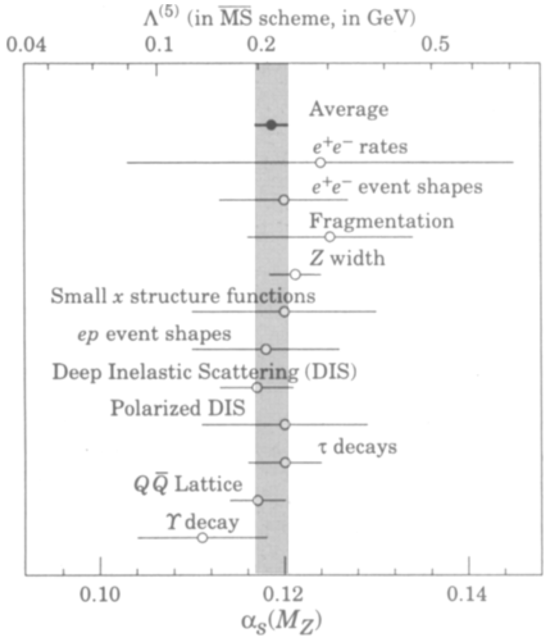

Figure 9.1: Summary of the values of $\alpha_s(M_Z)$ and $\Lambda^{(5)}$ from various processes. The values shown indicate the process and the measured value of α_s extrapolated up to $\mu = M_Z$. The error shown is the *total* error including theoretical uncertainties.

9.4. QCD in decays of the τ lepton

The semi-leptonic branching ratio of the tau ($\tau \to \nu_\tau + \text{hadrons}$, R_τ) is an inclusive quantity. It is related to the contribution of hadrons to the imaginary part of the W self energy $(\Pi(s))$. However, it is more inclusive than R since it involves an integral

$$R_\tau \sim \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}(1-\frac{s}{m_\tau^2})^2 \ \text{Im}\,(\Pi(s)) \ .$$

Since the scale involved is low, one must take into account nonperturbative (higher-twist) contributions which are suppressed by powers of the τ mass.

$$\begin{aligned} R_\tau =& 3.058\left[1+\frac{\alpha_s(m_\tau)}{\pi}+5.2\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^2+26.4\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^3\right. \\ &\left.+a\frac{m^2}{m_\tau^2}+b\frac{m\psi\overline{\psi}}{m_\tau^4}+c\frac{\psi\overline{\psi}\psi\overline{\psi}}{m_\tau^6}+\cdots\right] \ . \end{aligned} \tag{9.15}$$

Here a, b, and c are dimensionless constants and m is a light quark mass. The term of order $1/m_\tau^2$ is a kinematical effect due to the light quark masses and is consequently very small. The nonperturbative terms are estimated using sum rules [48]. In total, they are estimated to be -0.014 ± 0.005 [49,50]. This estimate relies on there being no term of order Λ^2/m_τ^2 $\left(\text{note that } \frac{\alpha_s(m_\tau)}{\pi} \sim (\frac{0.5 \text{ GeV}}{m_\tau})^2\right)$. The a, b, and c can be determined from the data [51] by fitting to moments of the $\Pi(s)$. The values so extracted [52,53] are consistent with the theoretical estimates. If the nonperturbative terms are omitted from the fit, the extracted value of $\alpha_s(m_\tau)$ decreases by ~ 0.02.

For $\alpha_s(m_\tau) = 0.35$ the perturbative series for R_τ is $R_\tau \sim 3.058(1 + 0.112 + 0.064 + 0.036)$. The size (estimated error) of the nonperturbative term is 20% (7%) of the size of the order α_s^3 term. The perturbation series in not very well convergent; if the order α_s^3 term is omitted, the extracted value of $\alpha_s(m_\tau)$ increases by 0.05. The order α_s^4 term has been estimated [54] and attempts made to resum the entire series [55,56]. These estimates can be used to obtain an estimate of the errors due to these unknown terms [57,58]. We assign an uncertainty of ± 0.02 to $\alpha_s(m_\tau)$ from these sources.

R_τ can be extracted from the semi-leptonic branching ratio from the relation $R_\tau = 1/(\text{B}(\tau \to e\nu\overline{\nu}) - 1.97256$; where $\text{B}(\tau \to e\nu\overline{\nu})$ is measured directly or extracted from the lifetime, the muon mass, and the muon lifetime assuming universality of lepton couplings. Using the average lifetime of 290.7 ± 1.3 fs and a τ mass of 1777.00 ± 0.30 MeV from the PDG fit gives $R_\tau = 3.642 \pm 0.024$. The direct measurement of $\text{B}(\tau \to e\nu\overline{\nu})$ can be combined with $\text{B}(\tau \to \mu\nu\overline{\nu})$ to give $\text{B}(\tau \to e\nu\overline{\nu}) = 0.1783 \pm 0.0007$ which $R_\tau = 3.636 \pm 0.021$. Averaging these yields $\alpha_s(m_\tau) = 0.350 \pm 0.008$ using the experimental error alone. We assign a theoretical error equal to 40% of the contribution from the order α^3 term and all of the nonperturbative contributions. This then gives $\alpha_s(m_\tau) = 0.35 \pm 0.03$ for the final result.

9.5. QCD in high-energy hadron collisions

There are many ways in which perturbative QCD can be tested in high-energy hadron colliders. The quantitative tests are only useful if the process in question has been calculated beyond leading order in QCD perturbation theory. The production of hadrons with large transverse momentum in hadron-hadron collisions provides a direct probe of the scattering of quarks and gluons: $qq \to qq$, $qg \to qg$, $gg \to gg$, *etc.* Recent higher–order QCD calculations of the jet rates [59] and shapes are in impressive agreement with data [60].This agreement has led to the proposal that these data could be used to provide a determination of α_s [61]. Data are also available on the angular distribution of jets; these are also in agreement with QCD expectations [62,63].

QCD corrections to Drell-Yan type cross sections (*i.e.*, the production in hadron collisions by quark-antiquark annihilation of lepton pairs of invariant mass Q from virtual photons, or of real W or Z bosons), are known [64]. These $\mathcal{O}(\alpha_s)$ QCD corrections are sizable at small values of Q. It is interesting to note that the corresponding correction to W and Z production, as measured in $p\overline{p}$ collisions at $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV, has essentially the same theoretical form and is of order 30%.

The production of W and Z bosons and photons at large transverse momentum can also be used to test QCD. The leading-order QCD subprocesses are $q\overline{q} \to \gamma g$ and $qg \to \gamma q$. If the parton distributions are taken from other processes and a value of $\Lambda^{(4)}_{\overline{\text{MS}}}$ assumed, then an absolute prediction is obtained. Conversely, the data can be used to extract information on quark and gluon distributions and on the value of $\Lambda^{(4)}_{\overline{\text{MS}}}$. The next-to-leading-order QCD corrections are known [65,66] (for photons), and for W/Z production [67], and so a precision test is possible in principle. Data exist from the CDF and DØ collaborations [68,69]. The UA2 collaboration [70] has extracted a value of $\alpha_s(M_W) = 0.123 \pm 0.018(\text{stat.}) \pm 0.017(\text{syst.})$ from the measured ratio $R_W = \frac{\sigma(W+1\text{jet})}{\sigma(W+0\text{jet})}$. The result depends on the algorithm used to define a jet, and the dominant systematic errors due to fragmentation and corrections for underlying events (the former causes jet energy to be lost, the latter causes it to be increased) are connected to the algorithm. The scale at which $\alpha_s(M)$ is to be evaluated is not clear. A change from $\mu = M_W$ to $\mu = M_W/2$ causes a shift of 0.01 in the extracted α_s. The quoted error should be increased to take this into account. There is dependence on the parton distribution functions, and hence, α_s appears explicitly in the formula for R_W, and implicitly in the distribution functions. The DØ collaboration has performed an analysis similar to UA2. They are unable to obtain a fit where the two values of α_s are consistent with one another, and do not quote a value of α_s [71]. The values from this process are no longer used in determining the overall average value of α_s.

9.6. QCD in heavy-quarkonium decay

Under the assumption that the hadronic and leptonic decay widths of heavy $Q\overline{Q}$ resonances can be factorized into a nonperturbative part—dependent on the confining potential—and a calculable perturbative part, the ratios of partial decay widths allow measurements of α_s at the heavy-quark mass scale. The most precise data come from the decay widths of the 1^{--} $J/\psi(1S)$ and Υ resonances. The total decay width of the Υ is predicted by perturbative QCD [72]

$$\begin{aligned} R_\mu(\Upsilon) &= \frac{\Gamma(\Upsilon \to \text{hadrons})}{\Gamma(\Upsilon \to \mu^+\mu^-)} \\ &= \frac{10(\pi^2-9)\alpha_s^3(M)}{9\pi\alpha_{\text{em}}^2} \\ &\quad \times \left[1 + \frac{\alpha_s}{\pi}\left(-19.4 + \frac{3\beta_0}{2}\left(1.162 + \ln\left(\frac{2M}{M_\Upsilon}\right)\right)\right)\right] \end{aligned} \tag{9.16}$$

Data are available for the Υ, Υ', Υ'', and J/ψ. The result is very sensitive to α_s and the data are sufficiently precise ($R_\mu(\Upsilon) = 32.5 \pm 0.9$) [73] that the theoretical errors will dominate. There are theoretical corrections to this simple formula due to the relativistic nature of the $Q\overline{Q}$ system; $v^2/c^2 \sim 0.1$ for the Υ. They are more severe for the J/ψ. There are also nonperturbative corrections of the form Λ^2/m_Υ^2; again these are more severe for the J/ψ. A fit to Υ, Υ', and Υ'' [74] gives $\alpha_s(M_Z) = 0.113 \pm 0.001$ (expt.). The results from each state separately and also from the J/ψ are consistent with each other. There is an uncertainty of order ± 0.005 from the choice of scale; the error from v^2/c^2 corrections is a little larger. The ratio of widths $\dfrac{\Upsilon \to \gamma gg}{\Upsilon \to ggg}$ has been measured by the CLEO collaboration who use it to determine $\alpha_s(9.45 \text{ GeV}) = 0.163 \pm 0.002 \pm 0.014$ [76] which corresponds to $\alpha_s(M_Z) = 0.110 \pm 0.001 \pm 0.007$. The error is dominated by theoretical uncertainties associated with the scale choice. The theoretical uncertainties due to the production of photons in fragmentation [75] are small [76].

9.7. Perturbative QCD in e^+e^- collisions

The total cross section for $e^+e^- \to$ hadrons is obtained (at low values of $\sqrt{s}$) by multiplying the muon-pair cross section by the factor $R = 3\Sigma_q e_q^2$. The higher-order QCD corrections to this quantity have been calculated, and the results can be expressed in terms of the factor:

$$R = R^{(0)}\left[1 + \frac{\alpha_s}{\pi} + C_2\left(\frac{\alpha_s}{\pi}\right)^2 + C_3\left(\frac{\alpha_s}{\pi}\right)^3 + \cdots\right], \tag{9.17}$$

where $C_2 = 1.411$ and $C_3 = -12.8$ [77].

$R^{(0)}$ can be obtained from the formula for $d\sigma/d\Omega$ for $e^+e^- \to f\overline{f}$ by integrating over Ω. The formula is given in Sec. 36.2 of this *Review*. This result is only correct in the zero-quark-mass limit. The $\mathcal{O}(\alpha_s)$ corrections are also known for massive quarks [78]. The principal advantage of determining α_s from R in e^+e^- annihilation is that there is no dependence on fragmentation models, jet algorithms, *etc.*

A comparison of the theoretical prediction of Eq. (9.17) (corrected for the b-quark mass), with all the available data at values of $\sqrt{s}$ between 20 and 65 GeV, gives [79] $\alpha_s(35 \text{ GeV}) = 0.146 \pm 0.030$. The size of the order α_s^3 term is of order 40% of that of the order α_s^2 and 3% of the order α_s. If the order α_s^3 term is not included, a fit to the data yields α_s (34 GeV) $= 0.142 \pm 0.03$, indicating that the theoretical uncertainty is smaller than the experimental error.

Measurements of the ratio of hadronic to leptonic width of the Z at LEP and SLC, Γ_h/Γ_μ probe, the same quantity as R. Using the average of $\Gamma_h/\Gamma_\mu = 20.783 \pm 0.029$ gives $\alpha_s(M_Z) = 0.124 \pm 0.0043$ [80]. There are theoretical errors arising from the values of top-quark and Higgs masses which enter due to electroweak corrections to the Z width and from the choice of scale.

While this method has small theoretical uncertainties from QCD itself, it relies sensitively on the electroweak couplings of the Z to quarks [81]. The presence of new physics which changes these couplings via electroweak radiative corrections would invalidate the value of $\alpha_s(M_Z)$. However, given the excellent agreement [82] of the many measurements at the Z, there is no reason not to use the value of $\alpha_s(M_Z) = 0.1214 \pm 0.0031$ from the global fits of the various precision measurements at LEP/SLC and the W and top masses in the world average (see the section on "Electroweak model and constraints on new physics," Sec. 10 of this *Review*)

An alternative method of determining α_s in e^+e^{-*}annihilation is from measuring quantities that are sensitive to the relative rates of two-, three-, and four-jet events. A recent review should be consulted for more details [83] of the issues mentioned briefly here. In addition to simply counting jets, there are many possible choices of such "shape variables": thrust [84], energy-energy correlations [85], average jet mass, *etc.* All of these are infrared safe, which means they can be reliably calculated in perturbation theory. The starting point for all these quantities is the multijet cross section. For example, at order α_s, for the process $e^+e^- \to q\overline{q}g$: [86]

$$\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}, \tag{9.18}$$

where

$$x_i = \frac{2E_i}{\sqrt{s}} \tag{9.19}$$

are the center-of-mass energy fractions of the final-state (massless) quarks. A distribution in a "three-jet" variable, such as those listed above, is obtained by integrating this differential cross section over an appropriate phase space region for a fixed value of the variable. The order α_s^2 corrections to this process have been computed, as well as the 4-jet final states such as $e^+e^- \to q\overline{q}gg$ [87].

There are many methods used by the e^+e^- experimental groups to determine α_s from the event topology. The jet-counting algorithm, originally introduced by the JADE collaboration [88], has been used by many other groups. Here, particles of momenta p_i and p_j are combined into a pseudo-particle of momentum $p_i + p_j$ if the invariant mass of the pair is less than $y_0\sqrt{s}$. The process is then iterated until no more pairs of particles or pseudo-particles remain. The remaining number is then defined to be the number of jets in the event, and can be compared to the QCD prediction. The Durham algorithm is slightly different: in computing the mass of a pair of partons, it uses $M^2 = 2\min(E_1^2, E_2^2)(1 - \cos\theta_{ij})$ for partons of energies E_i and E_j separated by angle θ_{ij} [89].

There are theoretical ambiguities in the way this process is carried out. Quarks and gluons are massless, whereas the observed hadrons are not, so that the massive jets that result from this scheme cannot be compared directly to the massless jets of perturbative QCD. Different recombination schemes have been tried, for example combining 3-momenta and then rescaling the energy of the cluster so that it remains massless. These schemes result in the same data giving a slightly different values [90,91] of α_s. These differences can be used to determine a systematic error. In addition, since what is observed are hadrons rather than quarks and gluons, a model is needed to describe the evolution of a partonic final state into one involving hadrons, so that detector corrections can be applied. The QCD matrix elements are combined with a parton-fragmentation model. This model can then be used to correct the data for a direct comparison with the parton calculation. The different hadronization models that are used [92–95] model the dynamics that are controlled by nonperturbative QCD effects which we cannot yet calculate. The fragmentation parameters of these Monte Carlos are tuned to get agreement with the observed data. The differences between these models contribute to the systematic errors. The systematic errors from recombination schemes and fragmentation effects dominate over the statistical and other errors of the LEP/SLD experiments.

The scale M at which $\alpha_s(M)$ is to be evaluated is not clear. The invariant mass of a typical jet (or $\sqrt{sy_0}$) is probably a more appropriate choice than the e^+e^- center-of-mass energy. While there is no justification for doing so, if the value is allowed to float in the fit to the data, the data tend to prefer values of order $\sqrt{s}/10$ GeV for some variables, whereas others have only a preferred range of $M > 3$ GeV [91,96]; the exact value depends on the variable that is fitted.

The perturbative QCD formulae can break down in special kinematical configurations. For example, the thrust distribution contains terms of the type $\alpha_s \ln^2(1-T)$. The higher orders in the perturbation expansion contain terms of order $\alpha_s^n \ln^m(1-T)$. For $T \sim 1$ (the region populated by 2-jet events), the perturbation expansion is unreliable. The terms with $n \leq m$ can be summed to all orders in α_s [97]. If the jet recombination methods are used higher-order terms involve $\alpha_s^n \ln^m(y_0)$, these too can be resummed [98]. The resummed results give better agreement with the data at large values of T. Some caution should be exercised in using these resummed results because of the possibility of overcounting; the showering Monte Carlos that are used for the fragmentation corrections also generate some of these leading-log corrections. Different schemes for combining the order α_s^2 and the resummations are available [99]. These different schemes result in shifts in α_s of order ± 0.002. An average of the recent results at the Z resonance from SLD [91], OPAL [100], L3 [101], ALEPH [102], and DELPHI [103], using the combined α_s^2 and resummation fitting to a large set of shape variables, gives $\alpha_s(M_Z) = 0.122 \pm 0.007$. The errors in the values of $\alpha_s(M_Z)$ from these shape variables are totally dominated by the theoretical uncertainties associated with the choice of scale, and the effects of hadronization Monte Carlos on the different quantities fitted.

Similar studies on event shapes have been undertaken at TRISTAN, at PEP/PETRA, and at CLEO. A combined result from various shape parameters by the TOPAZ collaboration gives $\alpha_s(58 \text{ GeV}) = 0.125 \pm 0.009$, using the fixed order QCD result, and $\alpha_s(58 \text{ GeV}) = 0.132 \pm 0.008$ (corresponding to $\alpha_s(M_Z) = 0.123 \pm 0.007$), using the same method as in the SLD and LEP average [104]. The measurements of event shapes at PEP/PETRA are summarized in earlier editions of this note. The results are consistent with those from Z decay, but have larger errors. We use $\alpha_s(34 \text{ GeV}) = 0.14 \pm 0.02$ [105]. A recent analysis by the TPC group [106] gives $\alpha_s(29 \text{ GeV}) = 0.160 \pm 0.012$, using the same method as TOPAZ. This value corresponds to $\alpha_s(M_Z) = 0.131 \pm 0.010$

The CLEO collaboration fits to the order α_s^2 results for the two jet fraction at $\sqrt{s} = 10.53$ GeV, and obtains $\alpha_s(10.93) = 0.164 \pm 0.004$ (expt.) ± 0.014 (theory) [107]. The dominant systematic error arises from the choice of scale (μ), and is determined from the range of α_s that results from fit with $\mu = 10.53$ GeV, and a fit where μ is allowed to vary to get the lowest χ^2. The latter results in $\mu = 1.2$ GeV. Since the quoted result corresponds to $\alpha_s(1.2) = 0.35$, it is by no means clear that the perturbative QCD expression is reliable and the resulting error should, therefore, be treated with caution. A fit to many different variables as is done in the LEP/SLC analyses would give added confidence to the quoted error.

Recently studies have been carried out at ~130 GeV [108]. These can be combined to give $\alpha_s(130 \text{ GeV}) = 0.114 \pm 0.008$. Preliminary data from ~ 165 GeV [109] are consistent with the decrease in α_s expected at the higher energy.

Since the errors in the event shape measurements are dominantly systematic, and are common to the experiments, the results from PEP/PETRA, TRISTAN, LEP, SLC, and CLEO are combined to give $\alpha_s(M_Z) = 0.121 \pm 0.007$. All of the experiments are consistent with this average and, taken together, provide verification of the running of the coupling constant with energy.

The total cross section $e^+e^- \to b\bar{b} + X$ near threshold can be used to determine α_s [110]. The result quoted is $\alpha_s(M_Z) = 0.109 \pm 0.001$. The relevant process is only calculated to leading order and the BLM scheme [9] is used. This results in $\alpha_s(0.632\ m_b)$. If $\alpha_s(m_b)$ is used, the resulting $\alpha_s(M_Z)$ shifts to ~ 0.117. This result is not used in the average.

9.8. Scaling violations in fragmentation functions

Measurements of the fragmentation function $d_i(z, E)$, being the probability that a hadron of type i be produced with energy zE in e^+e^- collisions at $\sqrt{s} = 2E$, can be used to determine α_s. As in the case of scaling violations in structure functions, QCD predicts only the E dependence. Hence, measurements at different energies are needed to extract a value of α_s. Because the QCD evolution mixes the fragmentation functions for each quark flavor with the gluon fragmentation function, it is necessary to determine each of these before α_s can be extracted. The ALEPH collaboration has used data from energies ranging from $\sqrt{s} = 22$ GeV to $\sqrt{s} = 91$ GeV. A flavor tag is used to discriminate between different quark species, and the longitudinal and transverse cross sections are used to extract the gluon fragmentation function [111]. The result obtained is $\alpha_s(M_Z) = 0.126 \pm 0.007$ (expt.) ± 0.006 (theory) [112]. The theory error is due mainly to the choice of scale. The OPAL collaboration [113] has also extracted the separate fragmentation functions. DELPHI [114] has also performed a similar analysis using data from other experiments at lower energy with the result $\alpha_s(M_Z) = 0.124 \pm 0.007 \pm 0.009$ (theory).The larger theoretical error is due to the larger range of scales that were used in the fit. These results can be combined to give $\alpha_s(M_Z) = 0.125 \pm 0.005 \pm 0.008$ (theory).

e^+e^- can also be used to study photon-photon interaction, which can be used to measure the structure function of a photon [115]. This process was included in earlier versions of this *Review* [115] which can be consulted for details on older measurements [116–119]. More recent data has become available from LEP [120,121] and from TRISTAN [122,123] which show Q^2 dependence of the structure function that is consistent with QCD expectations.

9.9. Jet rates in *ep* collisions

At lowest order in α_s, the *ep* scattering process produces a final state of (1+1) jets, one from the proton fragment and the other from the quark knocked out by the process $e + quark \to e + quark$. At next order in α_s, a gluon can be radiated, and hence a (2+1) jet final state produced. By comparing the rates for these (1+1) and (2+1) jet processes, a value of α_s can be obtained. A NLO QCD calculation is available [124]. The basic methodology is similar to that used in the jet counting experiments in e^+e^- annihilation discussed above. Unlike those measurements, the ones in *ep* scattering are not at a fixed value of Q^2. In addition to the systematic errors associated with the jet definitions, there are additional ones since the structure functions enter into the rate calculations. Results from H1 [125] and ZEUS [126] can be combined to give $\alpha_s(M_Z) = 0.118 \pm 0.001$ (expt.) ± 0.008 (syst.). The contributions to the systematic errors from experimental effects (mainly the hadronic energy scale) in the case of ZEUS (H1) are comparable to (smaller than) the theoretical ones arising from scale choice, structure functions, and jet definitions. The theoretical errors are common to the two measurements; therefore, we have not reduced the systematic error after forming the average.

9.10. Lattice QCD

Lattice gauge theory calculations can be used to calculate, using non-perturbative methods, a physical quantity that can be measured experimentally. The value of this quantity can then be used to determine the QCD coupling that enters in the calculation. For a recent review of the methodology see Ref. 127. For example, the energy levels of a $Q\overline{Q}$ system can be determined and then used to extract α_s. The masses of the $Q\overline{Q}$ states depend only on the quark mass and on α_s. A limitation is that calculations cannot be performed for three light quark flavors. Results are available for zero ($n_f = 0$, quenched approximation) and two light flavors, which allow extrapolation to three. The coupling constant so extracted is in a lattice renormalization scheme, and must be converted to the $\overline{\text{MS}}$ scheme for comparison with other results. Using the mass differences of Υ and Υ' and Υ'' and χ_b, Davies *et al.* [128] extract a value of $\alpha_s(M_Z) = 0.1174 \pm 0.0024$. A similar result with larger errors is reported by [129], where results are consistent with $\alpha_s(M_Z) = 0.111 \pm 0.006$. A combination of the results from quenched [130] and ($n_f = 2$) [131] gives $\alpha_s(M_Z) = 0.116 \pm 0.003$ [132].

Calculations [133] using the strength of the force between two heavy quarks computed in the quenched approximation obtains a value of $\alpha_s(5\text{ GeV})$ that is consistent with these results. There have also been investigations of the running of α_s [134]. These show remarkable agreement with the two loop perturbative result of Eq. (9.4).

There are several sources of error in these estimates of $\alpha_s(M_Z)$. The experimental error associated with the measurements of the particle masses is negligible. The conversion from the lattice coupling constant to the $\overline{\text{MS}}$ constant is obtained using a perturbative expansion where one coupling expanded as a power series in the other. This series is only known to second order. A third order calculation exists only from the $n_f = 0$ case [135]. Its inclusion leads to a shift in the extracted value of $\alpha_s(M_Z)$ of $+0.002$. Other theoretical errors arising from the limited statistics of the Monte-Carlo calculation, extrapolation in n_f, and corrections for light quark masses are smaller than this.

The result with a more conservative error $\alpha_s(M_Z) = 0.117 \pm 0.003$ will be used in the average.

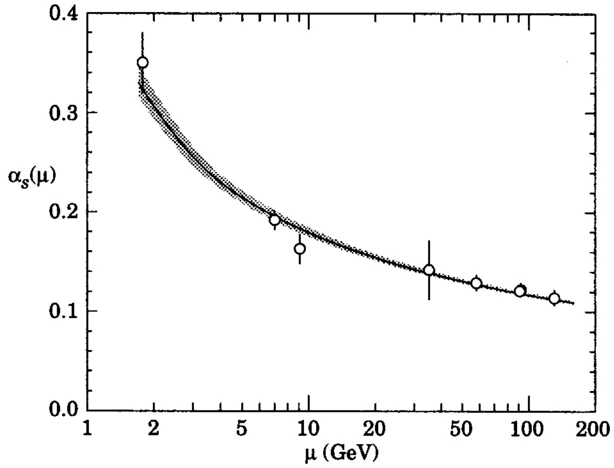

Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ.

9.11. Conclusions

The need for brevity has meant that many other important topics in QCD phenomenology have had to be omitted from this review. One should mention in particular the study of exclusive processes (form factors, elastic scattering, ...), the behavior of quarks and gluons in nuclei, the spin properties of the theory, the interface of soft and hard QCD as manifest, for example, by hard diffractive processes, and QCD effects in hadron spectroscopy.

We have focused on those high-energy processes which currently offer the most quantitative tests of perturbative QCD. Figure 9.1 shows the values of $\alpha_s(M_Z)$ deduced from the various experiments. Figure 9.2 shows the values and the values of Q where they are measured. This figure clearly shows the experimental evidence for the variation of $\alpha_s(Q)$ with Q.

An average of the values in Fig. 9.1 gives $\alpha_s(M_z) = 0.1189$, with a total χ^2 of 3.3 for eleven fitted points, showing good consistency among the data. The error on the average, assuming that all of the errors in the contributing results are uncorrelated, is ± 0.0015, and is an underestimate. Almost all of the values used in the average are dominated by systematic, usually theoretical errors. Only some of these, notably from the choice of scale, are correlated. Two of the results with the smallest errors are the ones from τ decay and lattice gauge theory. If these errors are increased to ± 0.006, the average is unchanged and the error increases to 0.0020. We quote our average value as $\alpha_s(M_Z) = 0.119 \pm 0.002$, which corresponds to $\Lambda^{(5)} = 219^{+25}_{-23}$ MeV using Eq. (9.5*a*), only the two-loop result (*i.e.* dropping the last term in Eq. (9.5*a*)) gives $\Lambda^{(5)} = 237^{+26}_{-24}$ MeV. Future experiments can be expected to improve the measurements of α_s somewhat. Precision at the 1% level may be achievable if the systematic and theoretical errors can be reduced [136].

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10. ELECTROWEAK MODEL AND CONSTRAINTS ON NEW PHYSICS

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10.1. Introduction

The standard electroweak model is based on the gauge group [1] SU(2) × U(1), with gauge bosons W_μ^i, $i = 1,2,3$, and B_μ for the SU(2) and U(1) factors, respectively, and the corresponding gauge coupling constants g and g'. The left-handed fermion fields $\psi_i = \binom{\nu_i}{\ell_i^-}$ and $\binom{u_i}{d_i'}$ of the i^{th} fermion family transform as doublets under SU(2), where $d_i' \equiv \sum_j V_{ij}\, d_j$, and V is the Cabibbo-Kobayashi-Maskawa mixing matrix. (Constraints on V are discussed in the section on the Cabibbo-Kobayashi-Maskawa mixing matrix.) The right-handed fields are SU(2) singlets. In the minimal model there are three fermion families and a single complex Higgs doublet $\phi \equiv \binom{\phi^+}{\phi^0}$.

After spontaneous symmetry breaking the Lagrangian for the fermion fields is

$$\begin{aligned}\mathscr{L}_F = &\sum_i \overline{\psi}_i \left(i\, \not\partial - m_i - \frac{g m_i H}{2M_W}\right)\psi_i \\ &- \frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i\, \gamma^\mu\,(1-\gamma^5)(T^+\, W_\mu^+ + T^-\, W_\mu^-)\,\psi_i \\ &- e\sum_i q_i\, \overline{\psi}_i\, \gamma^\mu\, \psi_i\, A_\mu \\ &- \frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i\, \gamma^\mu(g_V^i - g_A^i\gamma^5)\,\psi_i\, Z_\mu\ . \qquad (10.1)\end{aligned}$$

$\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle; $e = g\sin\theta_W$ is the positron electric charge; and $A \equiv B\cos\theta_W + W^3\sin\theta_W$ is the (massless) photon field. $W^\pm \equiv (W^1 \mp iW^2)/\sqrt{2}$ and $Z \equiv -B\sin\theta_W + W^3\cos\theta_W$ are the massive charged and neutral weak boson fields, respectively. T^+ and T^- are the weak isospin raising and lowering operators. The vector and axial couplings are

$$g_V^i \equiv t_{3L}(i) - 2q_i\sin^2\theta_W\ , \qquad (10.2)$$

$$g_A^i \equiv t_{3L}(i)\ , \qquad (10.3)$$

where $t_{3L}(i)$ is the weak isospin of fermion i (+1/2 for u_i and ν_i; −1/2 for d_i and e_i) and q_i is the charge of ψ_i in units of e.

The second term in $\mathscr{L}_F$ represents the charged-current weak interaction [2]. For example, the coupling of a W to an electron and a neutrino is

$$-\frac{e}{2\sqrt{2}\sin\theta_W}\left[W_\mu^-\, \overline{e}\, \gamma^\mu(1-\gamma^5)\nu + W_\mu^+\, \overline{\nu}\, \gamma^\mu\,(1-\gamma^5)e\right]\ . \qquad (10.4)$$

For momenta small compared to M_W, this term gives rise to the effective four-fermion interaction with the Fermi constant given (at tree level, *i.e.*, lowest order in perturbation theory) by $G_F/\sqrt{2} = g^2/8M_W^2$. CP violation is incorporated in the Standard Model by a single observable phase in V_{ij}. The third term in $\mathscr{L}_F$ describes electromagnetic interactions (QED), and the last is the weak neutral-current interaction.

In Eq. (10.1), m_i is the mass of the i^{th} fermion ψ_i. For the quarks these are the current masses. For the light quarks, as described in the Particle Listings, $\overline{m}_u \approx 2-8$ MeV, $\overline{m}_d \approx 5-15$ MeV, and $\overline{m}_s \approx 100-300$ MeV (these are running $\overline{\rm MS}$ masses evaluated at $\mu = 1$ GeV). For the heavier quarks, the $\overline{\rm MS}$ masses are $\overline{m}_c(\mu = \overline{m}_c) \approx 1.0-1.6$ GeV and $\overline{m}_b(\mu = \overline{m}_b) \approx 4.1-4.5$ GeV. The average of the recent CDF [4] and DØ [5] values for the top quark "pole" mass is $m_t = 175 \pm 5$ GeV. See "The Note on Quark Masses" in the Particle Listings for more information.

H is the physical neutral Higgs scalar which is the only remaining part of ϕ after spontaneous symmetry breaking. The Yukawa coupling of H to ψ_i, which is flavor diagonal in the minimal model, is $gm_i/2M_W$. The H mass is not predicted by the model. Experimental limits are given in the Higgs section. In nonminimal models there are additional charged and neutral scalar Higgs particles [6].

10.2. Renormalization and radiative corrections

The Standard Model has three parameters (not counting M_H and the fermion masses and mixings). A particularly useful set is:

(*a*) The fine structure constant $\alpha = 1/137.0359895$ (61), determined from the quantum Hall effect. In most electroweak-renormalization schemes, it is convenient to define a running α dependent on the energy scale of the process, with $\alpha^{-1} \sim 137$ appropriate at low energy. (The running has recently been observed directly [7].) At energies of order M_Z, $\alpha^{-1} \sim 128$. For example, in the modified minimal subtraction ($\overline{\rm MS}$) scheme [8], one has $\widehat{\alpha}(M_Z)^{-1} = 127.88 \pm 0.09$, while the conventional (on-shell) QED renormalization yields [9] $\alpha(M_Z)^{-1} = 128.88 \pm 0.09$, which differs by finite constants from $\widehat{\alpha}(M_Z)^{-1}$. The uncertainty, due to the low-energy hadronic contribution to vacuum polarization, is the dominant theoretical uncertainty in the interpretation of precision data. Other recent evaluations [10–14] of this effect are in reasonable agreement. Further improvement will require better measurements of the cross section for $e^+e^- \to$ hadrons at low energy.

(*b*) The Fermi constant, $G_F = 1.16639(1) \times 10^{-5}$ GeV^{-2}, determined from the muon lifetime formula [15],

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}\, F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right) \times \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right]\ , \qquad (10.5a)$$

where

$$F(x) = 1 - 8x + 8x^3 - x^4 - 12x^2\ln x\ , \qquad (10.5b)$$

and

$$\alpha(m_\mu)^{-1} = \alpha^{-1} - \frac{2}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \frac{1}{6\pi} \approx 136\ , \qquad (10.5c)$$

where the uncertainty in G_F is from the input quantities. There are additional uncertainties from higher order radiative corrections, which can be estimated from the magnitude of the known $\alpha^2\ln(m_\mu/m_e)$ term of $\sim 1.8 \times 10^{-10}$ (alternatively, one can view Eq. (10.5) as the exact definition of G_F; then the theoretical uncertainty appears instead in the formulae for quantities derived from G_F).

(*c*) $\sin^2\theta_W$, determined from the Z mass and other Z pole observables, the W mass, and neutral-current processes [16]. The value of $\sin^2\theta_W$ depends on the renormalization prescription. There are a number of popular schemes [18–23] leading to $\sin^2\theta_W$ values which differ by small factors which depend on m_t and M_H. The notation for these schemes is shown in Table 10.1. Discussion of the schemes follows the table.

(*i*) The on-shell scheme promotes the tree-level formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ to a definition of the renormalized $\sin^2\theta_W$ to all orders in perturbation theory, *i.e.*, $\sin^2\theta_W \to s_W^2 \equiv 1 - M_W^2/M_Z^2$. This scheme is simple conceptually. However, M_W is known much less precisely than M_Z and in practice one extracts s_W^2 from M_Z alone using

$$M_W = \frac{A_0}{s_W(1-\Delta r)^{1/2}}\ , \qquad (10.6a)$$

$$M_Z = \frac{M_W}{c_W}\ , \qquad (10.6b)$$

Table 10.1: Notations used to indicate the various schemes discussed in the text. Each definition of $\sin\theta_W$ leads to values that differ by small factors depending on m_t and M_H.

Scheme	Notation
On-shell	$s_W = \sin\theta_W$
NOV	$s_{M_Z} = \sin\theta_W$
$\overline{\text{MS}}$	$\widehat{s}_Z = \sin\theta_W$
$\overline{\text{MS}}$ *ND*	$\widehat{s}_{ND} = \sin\theta_W$
Effective angle	$\overline{s}_f = \sin\theta_W$

where $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$, $A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2} =$ 37.2802 GeV, and Δr includes the radiative corrections relating α, $\alpha(M_Z)$, G_F, M_W, and M_Z. One finds $\Delta r \sim \Delta r_0 - \rho_t/\tan^2\theta_W$, where $\Delta r_0 \approx 1 - \alpha/\alpha(M_Z) \approx 0.06$ is due to the running of α and $\rho_t = 3G_F m_t^2/8\sqrt{2}\pi^2 \approx 0.0096(m_t/175\text{ GeV})^2$ represents the dominant (quadratic) m_t dependence. There are additional contributions to Δr from bosonic loops, including those which depend logarithmically on the Higgs mass M_H. One has $\Delta r = 0.0349 \mp 0.0019 \pm 0.0007$ for $(m_t, M_H) = (175 \pm 5\text{ GeV}, M_Z)$, where the second uncertainty is from $\alpha(M_Z)$. Thus the value of s_W^2 extracted from M_Z includes a large uncertainty (∓ 0.0006) from the currently allowed range of m_t.

(*ii*) A more precisely determined quantity $s_{M_Z}^2$ can be obtained from M_Z by removing the (m_t, M_H) dependent term from Δr [19], *i.e.*,

$$s_{M_Z}^2 c_{M_Z}^2 \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2} . \tag{10.7}$$

This yields $s_{M_Z}^2 = 0.23116 \pm 0.00022$, with most of the uncertainty from α rather than M_Z. Scheme (*ii*) is equivalent to using M_Z rather than $\sin^2\theta_W$ as the third fundamental parameter. However, it recognizes that $s_{M_Z}^2$ is still a useful derived quantity. The small uncertainty in $s_{M_Z}^2$ compared to other schemes is because the m_t dependence has been removed by definition. However, the m_t uncertainty reemerges when other quantities (*e.g.*, M_W or other Z pole observables) are predicted in terms of M_Z.

Both s_W^2 and $s_{M_Z}^2$ depend not only on the gauge couplings but also on the spontaneous-symmetry breaking, and both definitions are awkward in the presence of any extension of the Standard Model which perturbs the value of M_Z (or M_W). Other definitions are motivated by the tree-level coupling constant definition $\theta_W = \tan^{-1}(g'/g)$.

(*iii*) In particular, the modified minimal subtraction ($\overline{\text{MS}}$) scheme introduces the quantity $\sin^2\widehat{\theta}_W(\mu) \equiv \widehat{g}'^2(\mu)/[\widehat{g}^2(\mu) + \widehat{g}'^2(\mu)]$, where the couplings $\widehat{g}$ and $\widehat{g}'$ are defined by modified minimal subtraction and the scale μ is conveniently chosen to be M_Z for electroweak processes. The value of $\widehat{s}_Z^2 = \sin^2\widehat{\theta}_W(M_Z)$ extracted from M_Z is less sensitive than s_W^2 to m_t (by a factor of $\tan^2\theta_W$), and is less sensitive to most types of new physics than s_W^2 or $s_{M_Z}^2$. It is also very useful for comparing with the predictions of grand unification. There are actually several variant definitions of $\sin^2\widehat{\theta}_W(M_Z)$, differing according to whether or how finite $\alpha\ln(m_t/M_Z)$ terms are decoupled (subtracted from the couplings). One cannot entirely decouple the $\alpha\ln(m_t/M_Z)$ terms from all electroweak quantities because $m_t \gg m_b$ breaks SU(2) symmetry. The scheme that will be adopted here decouples the $\alpha\ln(m_t/M_Z)$ terms from the $\gamma - Z$ mixing [8,20], essentially eliminating any $\ln(m_t/M_Z)$ dependence in the formulae for asymmetries at the Z pole when written in terms of $\widehat{s}_Z^2$. The various definitions are related by

$$\widehat{s}_Z^2 = c\,(m_t, M_H) s_W^2 = \overline{c}\,(m_t, M_H)\, s_{M_Z}^2 , \tag{10.8}$$

where $c = 1.0376 \pm 0.0021$ for $m_t = 175 \pm 5$ GeV and $M_H = M_Z$. Similarly, $\overline{c} = 1.0003 \mp 0.0007$. The quadratic m_t dependence is given by $c \sim 1 + \rho_t/\tan^2\theta_W$ and $\overline{c} \sim 1 - \rho_t/(1 - \tan^2\theta_W)$, respectively. The expressions for M_W and M_Z in the $\overline{\text{MS}}$ scheme are

$$M_W = \frac{A_0}{\widehat{s}_Z(1 - \Delta\widehat{r}_W)^{1/2}} , \tag{10.9a}$$

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2}\widehat{c}_Z} . \tag{10.9b}$$

One predicts $\Delta\widehat{r}_W = 0.0698 \pm 0.0001 \pm 0.0007$ for $m_t = 175 \pm 5$ GeV and $M_H = M_Z$. $\Delta\widehat{r}_W$ has no quadratic m_t dependence, because shifts in M_W are absorbed into the observed G_F, so that the error in $\Delta\widehat{r}_W$ is dominated by $\Delta r_0 = 1 - \alpha/\alpha(M_Z)$, which induces the second quoted uncertainty. Similarly, $\widehat{\rho} \sim 1 + \rho_t$. Including bosonic loops, $\widehat{\rho} = 1.0109 \pm 0.0006$ for $(m_t, M_H) = (175 \pm 5\text{ GeV}, M_Z)$.

(*iv*) A variant $\overline{\text{MS}}$ quantity $\widehat{s}_{\text{ND}}^2$ (used in the 1992 edition of this *Review*) does not decouple the $\alpha\ln(m_t/M_Z)$ terms [21]. It is related to $\widehat{s}_Z^2$ by

$$\widehat{s}_Z^2 = \widehat{s}_{\text{ND}}^2 \Big/ \left(1 + \frac{\widehat{\alpha}}{\pi}d\right) , \tag{10.10a}$$

$$d = \frac{1}{3}\left(\frac{1}{\widehat{s}^2} - \frac{8}{3}\right)\left[(1 + \frac{\widehat{\alpha}_s}{\pi})\ln\frac{m_t}{M_Z} - \frac{15\widehat{\alpha}_s}{8\pi}\right] \tag{10.10b}$$

where $\widehat{\alpha}_s$ is the QCD coupling at M_Z. Thus, $\widehat{s}_Z^2 - \widehat{s}_{\text{ND}}^2 \sim -0.0002$ for $m_t = 175$ GeV.

(*v*) Yet another definition, the effective angle [22,23] $\overline{s}_f^2$ for Z coupling to fermion f, is described at the end of Sec. 10.3.

Experiments are now at such a level of precision that complete $\mathcal{O}(\alpha)$ radiative corrections must be applied. For neutral-current and Z pole processes, these corrections are conveniently divided into two classes:

1. QED diagrams involving the emission of real photons or the exchange of virtual photons in loops, but not including vacuum polarization diagrams. These graphs often yield finite and gauge-invariant contributions to observable processes. However, they are dependent on energies, experimental cuts, *etc.*, and must be calculated individually for each experiment.
2. Electroweak corrections, including $\gamma\gamma$, γZ, ZZ, and WW vacuum polarization diagrams, as well as vertex corrections, box graphs, *etc.*, involving virtual W's and Z's. Many of these corrections are absorbed into the renormalized Fermi constant defined in Eq. (10.5). Others modify the tree-level expressions for Z pole observables and neutral-current amplitudes in several ways [16]. One-loop corrections are included for all processes. In addition, certain two-loop corrections are also important. In particular, two-loop corrections involving the top-quark modify ρ_t in $\widehat{\rho}$, Δr, and elsewhere by

$$\rho_t \to \rho_t[1 + R(M_H, m_t)\rho_t/3] . \tag{10.11}$$

$R(M_H, m_t)$ is best described as an expansion in M_Z^2/m_t^2. The unsuppressed terms were first obtained in Ref. 24, and are known analytically [25]. Contributions proportional to M_Z^2/m_t^2 were studied in Ref. 26 with the help of small and large Higgs mass expansions, which can be interpolated. These contributions are about as large as the leading ones in Refs. 24 and 25. Very recently, a subset of the relevant two-loop diagrams has been calculated numerically without any heavy mass expansion [27]. This serves as a valuable check on the M_H dependence of the leading terms obtained in Refs. 24–26. The difference turned out to be small. For M_H above its lower direct limit, $-17 < R < -11$. Mixed QCD-electroweak loops of order $\alpha\alpha_s m_t^2$ [28] and $\alpha\alpha_s^2 m_t^2$ [29]

increase the predicted value of m_t by 6%. This is, however, almost entirely an artifact of using the pole mass definition for m_t. The equivalent corrections when using the $\overline{\rm MS}$ definition $\overline{m}_t(\overline{m}_t)$ increase m_t by less than 0.5%. The leading electroweak [24,25] and mixed [30] two-loop terms are also known for the $Z \to b\bar{b}$ vertex, but not the respective subleading ones.

10.3. Cross-section and asymmetry formulas

It is convenient to write the four-fermion interactions relevant to ν-hadron, νe, and parity violating e-hadron neutral-current processes in a form that is valid in an arbitrary gauge theory (assuming massless left-handed neutrinos). One has

$$-\mathscr{L}^{\nu\text{Hadron}} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}\,\gamma^\mu\,(1-\gamma^5)\nu$$

$$\times \sum_i \left[\epsilon_L(i)\,\overline{q}_i\,\gamma_\mu(1-\gamma^5)q_i + \epsilon_R(i)\,\overline{q}_i\,\gamma_\mu(1+\gamma^5)q_i\right] \,, \qquad (10.12)$$

$$-\mathscr{L}^{\nu e} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}_\mu\,\gamma^\mu(1-\gamma^5)\nu_\mu\,\overline{e}\,\gamma_\mu(g_V^{\nu e} - g_A^{\nu e}\gamma^5)e \qquad (10.13)$$

(for $\nu_e e$ or $\overline{\nu}_e e$, the charged-current contribution must be included), and

$$-\mathscr{L}^{e\text{Hadron}} = -\frac{G_F}{\sqrt{2}}$$

$$\times \sum_i \left[C_{1i}\,\overline{e}\,\gamma_\mu\,\gamma^5\,e\,\overline{q}_i\,\gamma^\mu\,q_i + C_{2i}\,\overline{e}\,\gamma_\mu\,e\,\overline{q}_i\,\gamma^\mu\,\gamma^5\,q_i\right] \,. \qquad (10.14)$$

(One must add the parity-conserving QED contribution.)

The Standard Model expressions for $\epsilon_{L,R}(i)$, $g_{V,A}^{\nu e}$, and C_{ij} are given in Table 10.2. Note that $g_{V,A}^{\nu e}$ and the other quantities are coefficients of effective four-fermi operators, which differ from the quantities defined in Eq. (10.2) and Eq. (10.3) in the radiative corrections and in the presence of possible physics beyond the Standard Model.

A precise determination of the on-shell s_W^2, which depends only very weakly on m_t and M_H, is obtained from deep inelastic neutrino scattering from (approximately) isoscalar targets [31]. The ratio $R_\nu \equiv \sigma_{\nu N}^{NC}/\sigma_{\nu N}^{CC}$ of neutral- to charged-current cross sections has been measured to 1% accuracy by the CDHS [32] and CHARM [33] collaborations at CERN [34], and the CCFR collaboration at Fermilab [35,36] has obtained an even more precise result, so it is important to obtain theoretical expressions for R_ν and $R_{\overline{\nu}} \equiv \sigma_{\overline{\nu} N}^{NC}/\sigma_{\overline{\nu} N}^{CC}$ (as functions of $\sin^2\theta_W$) to comparable accuracy. Fortunately, most of the uncertainties from the strong interactions and neutrino spectra cancel in the ratio.

A simple zeroth-order approximation is

$$R_\nu = g_L^2 + g_R^2 r \,, \qquad (10.15a)$$

$$R_{\overline{\nu}} = g_L^2 + \frac{g_R^2}{r} \,, \qquad (10.15b)$$

where

$$g_L^2 \equiv \epsilon_L\,(u)^2 + \epsilon_L\,(d)^2 \approx \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \,, \qquad (10.16a)$$

$$g_R^2 \equiv \epsilon_R\,(u)^2 + \epsilon_R\,(d)^2 \approx \frac{5}{9}\sin^4\theta_W \,, \qquad (10.16b)$$

and $r \equiv \sigma_{\overline{\nu} N}^{CC}/\sigma_{\nu N}^{CC}$ is the ratio of $\overline{\nu}$ and ν charged-current cross sections, which can be measured directly. (In the simple parton model, ignoring hadron energy cuts, $r \approx (\frac{1}{3}+\epsilon)/(1+\frac{1}{3}\epsilon)$, where $\epsilon \sim 0.125$ is the ratio of the fraction of the nucleon's momentum carried by antiquarks to that carried by quarks.) In practice, Eq. (10.15) must be corrected for quark mixing, quark sea effects, c-quark threshold effects, nonisoscalarity, $W-Z$ propagator differences, the finite muon mass, QED and electroweak radiative corrections. Details of the neutrino spectra, experimental cuts, x and Q^2 dependence of structure functions, and longitudinal structure functions enter only at the level of these corrections and therefore lead to very small uncertainties. The largest theoretical uncertainty is associated with the c-threshold, which mainly affects σ^{CC}. Using the slow rescaling prescription [37] the central value of $\sin^2\theta_W$ from CCFR varies as $0.0111(m_c\,[\text{GeV}] - 1.31)$, where m_c is the effective mass. For $m_c = 1.31 \pm 0.24$ GeV (determined from ν-induced dimuon production [38]) this contributes ±0.003 to the total uncertainty $\Delta\sin^2\theta_W \sim \pm0.004$. This would require a high-energy neutrino beam for improvement. (The experimental uncertainty is also ±0.003). The CCFR group quotes $s_W^2 = 0.2236 \pm 0.0041$ for $(m_t, M_H) = (175, 150)$ GeV with very little sensitivity to (m_t, M_H). Combining all of the precise deep-inelastic measurements, one obtains $s_W^2 = 0.2260 \pm 0.0039$.

Table 10.2: Standard Model expressions for the neutral-current parameters for ν-hadron, νe, and e-hadron processes. At tree level, $\rho = \kappa = 1$, $\lambda = 0$. If radiative corrections are included, $\rho_{\nu N}^{NC} = 1.0084$, $\widehat{\kappa}_{\nu N} = 0.9964$ (at $\langle Q^2\rangle = 35$ GeV^2), $\lambda_{uL} = -0.0031$, $\lambda_{dL} = -0.0025$, and $\lambda_{dR} = 2\,\lambda_{uR} = 7.5 \times 10^{-5}$ for $m_t = 175$ GeV and $M_H = M_Z = 91.1867$ GeV. For νe scattering, $\rho_{\nu e} = 1.0130$ and $\widehat{\kappa}_{\nu e} = 0.9970$ (at $\langle Q^2\rangle = 0.$). For atomic parity violation and the SLAC polarized electron experiment, $\rho'_{eq} = 0.9879$, $\rho_{eq} = 1.0009$, $\widehat{\kappa}'_{eq} = 1.0029$, $\widehat{\kappa}_{eq} = 1.0304$, $\lambda_{1d} = -2\,\lambda_{1u} = 3.7 \times 10^{-5}$, $\lambda_{2u} = -0.0121$ and $\lambda_{2d} = 0.0026$. The dominant m_t dependence is given by $\rho \sim 1 + \rho_t$, while $\widehat{\kappa} \sim 1$ ($\overline{\rm MS}$) or $\kappa \sim 1 + \rho_t/\tan^2\theta_W$ (on-shell).

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho_{\nu N}^{NC}\left(\frac{1}{2} - \frac{2}{3}\widehat{\kappa}_{\nu N}\,\widehat{s}_Z^2\right) + \lambda_{uL}$
$\epsilon_L(d)$	$\rho_{\nu N}^{NC}\left(-\frac{1}{2} + \frac{1}{3}\widehat{\kappa}_{\nu N}\,\widehat{s}_Z^2\right) + \lambda_{dL}$
$\epsilon_R(u)$	$\rho_{\nu N}^{NC}\left(-\frac{2}{3}\widehat{\kappa}_{\nu N}\,\widehat{s}_Z^2\right) + \lambda_{uR}$
$\epsilon_R(d)$	$\rho_{\nu N}^{NC}\left(\frac{1}{3}\widehat{\kappa}_{\nu N}\,\widehat{s}_Z^2\right) + \lambda_{dR}$
$g_V^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2} + 2\widehat{\kappa}_{\nu e}\,\widehat{s}_Z^2\right)$
$g_A^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2}\right)$
C_{1u}	$\rho'_{eq}\left(-\frac{1}{2} + \frac{4}{3}\widehat{\kappa}'_{eq}\,\widehat{s}_Z^2\right) + \lambda_{1u}$
C_{1d}	$\rho'_{eq}\left(\frac{1}{2} - \frac{2}{3}\widehat{\kappa}'_{eq}\,\widehat{s}_Z^2\right) + \lambda_{1d}$
C_{2u}	$\rho_{eq}\left(-\frac{1}{2} + 2\widehat{\kappa}_{eq}\,\widehat{s}_Z^2\right) + \lambda_{2u}$
C_{2d}	$\rho_{eq}\left(\frac{1}{2} - 2\widehat{\kappa}_{eq}\,\widehat{s}_Z^2\right) + \lambda_{2d}$

The laboratory cross section for $\nu_\mu e \to \nu_\mu e$ or $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ elastic scattering is

$$\frac{d\sigma_{\nu_\mu,\overline{\nu}_\mu}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}$$

$$\times \left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + (g_V^{\nu e} \mp g_A^{\nu e})^2(1-y)^2 \right.$$

$$\left. -(g_V^{\nu e2} - g_A^{\nu e2})\frac{y\,m_e}{E_\nu}\right] \,, \qquad (10.17)$$

where the upper (lower) sign refers to $\nu_\mu(\overline{\nu}_\mu)$, and $y \equiv E_e/E_\nu$ (which runs from 0 to $(1 + m_e/2E_\nu)^{-1}$) is the ratio of the kinetic energy of the recoil electron to the incident ν or $\overline{\nu}$ energy. For $E_\nu \gg m_e$ this yields a total cross section

$$\sigma = \frac{G_F^2\,m_e\,E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + \frac{1}{3}(g_V^{\nu e} \mp g_A^{\nu e})^2\right] \,. \qquad (10.18)$$

The most accurate leptonic measurements [39–41] of $\sin^2\theta_W$ are from the ratio $R \equiv \sigma_{\nu_\mu e}/\sigma_{\overline{\nu}_\mu e}$ in which many of the systematic uncertainties cancel. Radiative corrections (other than m_t effects) are small compared to the precision of present experiments and have negligible effect on the extracted $\sin^2\theta_W$. The most precise experiment (CHARM II) [41] determined not only $\sin^2\theta_W$ but $g_{V,A}^{\nu e}$ as well. The cross sections for $\nu_e e$ and $\overline{\nu}_e e$ may be obtained from

Eq. (10.17) by replacing $g_{V,A}^{\nu e}$ by $g_{V,A}^{\nu e}+1$, where the 1 is due to the charged-current contribution.

The SLAC polarized-electron experiment [42] measured the parity-violating asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \; , \tag{10.19}$$

where $\sigma_{R,L}$ is the cross section for the deep-inelastic scattering of a right- or left-handed electron: $e_{R,L}N \to eX$. In the quark parton model

$$\frac{A}{Q^2} = a_1 + a_2 \frac{1-(1-y)^2}{1+(1-y)^2} \; , \tag{10.20}$$

where $Q^2 > 0$ is the momentum transfer and y is the fractional energy transfer from the electron to the hadrons. For the deuteron or other isoscalar targets, one has, neglecting the s-quark and antiquarks,

$$a_1 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{1u} - \frac{1}{2}C_{1d}\right) \approx \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(-\frac{3}{4}+\frac{5}{3}\sin^2\theta_W\right) \; , \tag{10.21a}$$

$$a_2 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{2u} - \frac{1}{2}C_{2d}\right) \approx \frac{9G_F}{5\sqrt{2}\pi\alpha}\left(\sin^2\theta_W - \frac{1}{4}\right) \; . \tag{10.21b}$$

There are now precise experiments measuring atomic parity violation [43] in cesium (at the 0.4% level) [44], thallium [45], lead [46], and bismuth [47]. The uncertainties associated with atomic wave functions are quite small for cesium, for which they are ~ 1% [48]. The theoretical uncertainties are 3% for thallium [49] but larger for the other atoms. For heavy atoms one determines the "weak charge"

$$\begin{aligned} Q_W &= -2\left[C_{1u}\,(2Z+N) + C_{1d}(Z+2N)\right] \\ &\approx Z(1-4\sin^2\theta_W) - N \; . \end{aligned} \tag{10.22}$$

The recent Boulder experiment in cesium also observed the parity-violating weak corrections to the nuclear electromagnetic vertex (the anapole moment [50]).

In the future it should be possible to reduce the theoretical wave function uncertainties by taking the ratios of parity violation in different isotopes [43,51]. There would still be some residual uncertainties from differences in the neutron charge radii, however [52].

The forward-backward asymmetry for $e^+e^- \to \ell^+\ell^-$, $\ell = \mu$ or τ, is defined as

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \; , \tag{10.23}$$

where $\sigma_F(\sigma_B)$ is the cross section for ℓ^- to travel forward (backward) with respect to the e^- direction. A_{FB} and R, the total cross section relative to pure QED, are given by

$$R = F_1 \; , \tag{10.24}$$

$$A_{FB} = 3F_2/4F_1 \; , \tag{10.25}$$

where

$$F_1 = 1 - 2\chi_0\, g_V^e\, g_V^\ell\, \cos\delta_R + \chi_0^2\left(g_V^{e2}+g_A^{e2}\right)\left(g_V^{\ell 2}+g_A^{\ell 2}\right) , \tag{10.26a}$$

$$F_2 = -2\chi_0\, g_A^e\, g_A^\ell\, \cos\delta_R + 4\chi_0^2\, g_A^e\, g_A^\ell\, g_V^e\, g_V^\ell \; , \tag{10.26b}$$

$$\tan\delta_R = \frac{M_Z\Gamma_Z}{M_Z^2 - s} \; , \tag{10.27}$$

$$\chi_0 = \frac{G_F}{2\sqrt{2}\pi\alpha}\frac{sM_Z^2}{\left[(M_Z^2-s)^2 + M_Z^2\Gamma_Z^2\right]^{1/2}} \; , \tag{10.28}$$

and $\sqrt{s}$ is the CM energy. Eq. (10.26) is valid at tree level. If the data is radiatively corrected for QED effects (as described above), then the remaining electroweak corrections can be incorporated [53,54] (in an approximation adequate for existing PEP, PETRA, and TRISTAN data, which are well below the Z pole) by replacing χ_0 by $\chi(s) \equiv (1+\rho_t)\chi_0(s)\alpha/\alpha(s)$, where $\alpha(s)$ is the running QED coupling, and evaluating g_V in the $\overline{\rm MS}$ scheme. Formulas for $e^+e^- \to$ hadrons may be found in Ref. 55.

At LEP and SLC, there are high-precision measurements of various Z pole observables [56–61]. These include the Z mass and total width, Γ_Z, and partial widths $\Gamma(f\overline{f})$ for $Z \to f\overline{f}$ where fermion $f = e$, μ, τ, hadrons, b, or c. The data is consistent with lepton-family universality, $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-) = \Gamma(\tau^+\tau^-)$, so one may work with an average width $\Gamma(\ell^+\ell^-)$. It is convenient to use the variables M_Z, Γ_Z, $R_\ell \equiv \Gamma({\rm had})/\Gamma(\ell^+\ell^-)$, $\sigma_{\rm had} \equiv 12\pi\Gamma(e^+e^-)\Gamma({\rm had})/M_Z^2\Gamma_Z^2$, $R_b \equiv \Gamma(b\overline{b})/\Gamma({\rm had})$, and $R_c \equiv \Gamma(c\overline{c})/\Gamma({\rm had})$, most of which are weakly correlated experimentally. (Γ(had) is the partial width into hadrons.) The largest correlation coefficient of −0.20 occurs between R_b and R_c. R_ℓ is insensitive to m_t except for the $Z \to b\overline{b}$ vertex and final state corrections and the implicit dependence through $\sin^2\theta_W$. Thus it is especially useful for constraining α_s. The width for invisible decays [57], $\Gamma({\rm inv}) = \Gamma_Z - 3\Gamma(\ell^+\ell^-) - \Gamma({\rm had}) = 500.1 \pm 1.8$ MeV, can be used to determine the number of neutrino flavors much lighter than $M_Z/2$, $N_\nu = \Gamma({\rm inv})/\Gamma^{\rm theory}(\nu\overline{\nu}) = 2.990 \pm 0.011$ for $(m_t, M_H) = (175 \pm 5\ {\rm GeV}, M_Z)$.

There are also measurements of various Z pole asymmetries. These include the polarization or left-right asymmetry

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \; , \tag{10.29}$$

where $\sigma_L(\sigma_R)$ is the cross section for a left- (right)-handed incident electron. A_{LR} has been measured precisely by the SLD collaboration at the SLC [59], and has the advantages of being extremely sensitive to $\sin^2\theta_W$ and that systematic uncertainties largely cancel. In addition, the SLD collaboration has extracted the final-state couplings A_b, A_c, A_τ, and A_μ from left-right forward-backward asymmetries [57,60], using

$$A_{LR}^{FB}(f) = \frac{\sigma_{LF}^f - \sigma_{LB}^f - \sigma_{RF}^f + \sigma_{RB}^f}{\sigma_{LF}^f + \sigma_{LB}^f + \sigma_{RF}^f + \sigma_{RB}^f} = \frac{3}{4}A_f \; , \tag{10.30}$$

where, for example, σ_{LF} is the cross section for a left-handed incident electron to produce a fermion f traveling in the forward hemisphere. Similarly, A_τ is measured at LEP [57] through the negative total τ polarization, $\mathcal{P}_\tau$, and A_e is extracted from the angular distribution of $\mathcal{P}_\tau$. An equation such as (10.30) assumes that initial state QED corrections, photon exchange, $\gamma - Z$ interference, the tiny electroweak boxes, and corrections for $\sqrt{s} \neq M_Z$ are removed from the data, leaving the pure electroweak asymmetries. This allows the use of effective tree-level expressions,

$$A_{LR} = A_eP_e \; , \tag{10.31}$$

$$A_{FB} = \frac{3}{4}A_f\frac{A_e + P_e}{1 + P_eA_e} \; , \tag{10.32}$$

where

$$A_f \equiv \frac{2\overline{g}_V^f\,\overline{g}_A^f}{\overline{g}_V^{f2} + \overline{g}_A^{f2}} \; , \tag{10.33}$$

and

$$\overline{g}_V^f = \sqrt{\rho_f}\,(t_{3L}^{(f)} - 2q_f\kappa_f\sin^2\theta_W) \; , \tag{10.33b}$$

$$\overline{g}_A^f = \sqrt{\rho_f}\,t_{3L}^{(f)} \; . \tag{10.33c}$$

P_e is the initial e^- polarization, so that the second equality in Eq. (10.30) is reproduced for $P_e = 1$, and the Z pole forward-backward asymmetries at LEP ($P_e = 0$) are given by $A_{FB}^{(0,f)} = \frac{3}{4}A_eA_f$ where $f = e$, μ, τ, b, c, s, and q, and where $A_{FB}^{(0,q)}$ refers to the hadronic charge asymmetry. The initial state coupling, A_e, is also determined through the left-right charge asymmetry [61] and in polarized Bhabba scattering [60] at the SLC.

The electroweak-radiative corrections have been absorbed into corrections $\rho_f - 1$ and $\kappa_f - 1$, which depend on the fermion f and on the renormalization scheme. In the on-shell scheme, the quadratic m_t dependence is given by $\rho_f \sim 1 + \rho_t$, $\kappa_f \sim 1 + \rho_t/\tan^2\theta_W$, while in $\overline{\rm MS}$, $\widehat{\rho}_f \sim \widehat{\kappa}_f \sim 1$, for $f \neq b$ ($\widehat{\rho}_b \sim 1 - \frac{4}{3}\rho_t$, $\widehat{\kappa}_b \sim 1 + \frac{2}{3}\rho_t$). In the $\overline{\rm MS}$ scheme the normalization is changed according to $G_FM_Z^2/2\sqrt{2}\pi \to \widehat{\alpha}/4\widehat{s}_Z^2\widehat{c}_Z^2$.

(If one continues to normalize amplitudes by $G_F M_Z^2/2\sqrt{2}\pi$, as in the 1996 edition of this *Review*, then $\hat{\rho}_f$ contains an additional factor of $\hat{\rho}$.) In practice, additional bosonic and fermionic loops, vertex corrections, leading higher order contributions, *etc.*, must be included. For example, in the $\overline{\mathrm{MS}}$ scheme one has, for $(m_t, M_H) = (175\ \mathrm{GeV}, M_Z)$, $\widehat{\rho}_\ell = 0.9978$, $\widehat{\kappa}_\ell = 1.0013$, $\widehat{\rho}_b = 0.9868$ and $\widehat{\kappa}_b = 1.0067$. It is convenient to define an effective angle $\overline{s}_f^2 \equiv \sin^2 \overline{\theta}_{Wf} \equiv \widehat{\kappa}_f \widehat{s}_Z^2 = \kappa_f s_W^2$, in terms of which $\overline{g}_V^f$ and $\overline{g}_A^f$ are given by $\sqrt{\rho_f}$ times their tree-level formulae. Because $\overline{g}_V^\ell$ is very small, not only $A_{LR}^0 = A_e$, $A_{FB}^{(0,\ell)}$, and $\mathcal{P}_\tau$, but also $A_{FB}^{(0,b)}$, $A_{FB}^{(0,c)}$, $A_{FB}^{(0,s)}$, and the hadronic asymmetries are mainly sensitive to $\overline{s}_\ell^2$. One finds that $\widehat{\kappa}_f$ $(f \neq b)$ is almost independent of (m_t, M_H), so that one can write

$$\overline{s}_\ell^2 \sim \widehat{s}_Z^2 + 0.00029\ . \tag{10.34}$$

Thus, the asymmetries determine values of $\overline{s}_\ell^2$ and $\widehat{s}_Z^2$ almost independent of m_t, while the κ's for the other schemes are m_t dependent.

10.4. *W* and *Z* decays

The partial decay width for gauge bosons to decay into massless fermions $f_1 \overline{f}_2$ is

$$\Gamma(W^+ \to e^+ \nu_e) = \frac{G_F M_W^3}{6\sqrt{2}\pi} \approx 226.5 \pm 0.3\ \ \mathrm{MeV}\ \ , \tag{10.35a}$$

$$\Gamma(W^+ \to u_i \overline{d}_j) = \frac{C G_F M_W^3}{6\sqrt{2}\pi}\, |V_{ij}|^2 \approx (707 \pm 1)\, |V_{ij}|^2\ \ \mathrm{MeV}\ \ , \tag{10.35b}$$

$$\Gamma(Z \to \psi_i \overline{\psi}_i) = \frac{C G_F M_Z^3}{6\sqrt{2}\pi} \left[g_V^{i2} + g_A^{i2} \right] \tag{10.35c}$$

$$\approx \begin{cases} 167.25 \pm 0.08\ \ \mathrm{MeV}\ (\nu\overline{\nu}), & 84.01 \pm 0.05\ \ \mathrm{MeV}\ (e^+e^-), \\ 300.3 \pm 0.2\ \ \mathrm{MeV}\ (u\overline{u}), & 383.1 \pm 0.2\ \ \mathrm{MeV}\ (d\overline{d}), \\ 376.0 \mp 0.1\ \ \mathrm{MeV}\ (b\overline{b}), & \end{cases}$$

where the numerical values are for $(m_t, M_H) = (175 \pm 5\ \mathrm{GeV}, M_Z)$. For leptons $C = 1$, while for quarks $C = 3\Big(1 + \alpha_s(M_V)/\pi + 1.409\alpha_s^2/\pi^2 - 12.77\alpha_s^3/\pi^3\Big)$, where the 3 is due to color and the factor in parentheses represents the universal part of the QCD corrections [62] for massless quarks [63]. The $Z \to f\overline{f}$ widths contain a number of additional corrections: universal (non-singlet) top-mass contributions [64]; fermion mass effects and further QCD corrections proportional to m_q^2 [65] (m_q is the running quark mass evaluated at the Z scale) which are different for vector and axial-vector partial widths; and singlet contributions starting from two-loop order which are large, strongly top-mass dependent, family universal, and flavor non-universal [66]. All QCD effects are known and included up to three loop order. The QED factor $1 + 3\alpha q_f^2/4\pi$, as well as two-loop $\alpha\alpha_s$ and α^2 corrections [67,68] are also included. Working in the on-shell scheme, *i.e.*, expressing the widths in terms of $G_F M_{W,Z}^3$, incorporates the largest radiative corrections from the running QED coupling [18,69]. Electroweak corrections to the Z widths are then incorporated by replacing $g_{V,A}^{i2}$ by $\overline{g}_{V,A}^{i2}$. Hence, in the on-shell scheme the Z widths are proportional to $\rho_i \sim 1 + \rho_t$. The $\overline{\mathrm{MS}}$ normalization (see the end of the previous section) accounts also for the leading electroweak corrections [22]. There is additional (negative) quadratic m_t dependence in the $Z \to b\overline{b}$ vertex corrections [70] which causes $\Gamma(b\overline{b})$ to decrease with m_t. The dominant effect is to multiply $\Gamma(b\overline{b})$ by the vertex correction $1 + \delta\rho_{b\overline{b}}$, where $\delta\rho_{b\overline{b}} \sim 10^{-2}(-\frac{1}{2}\frac{m_t^2}{M_Z^2} + \frac{1}{5})$. In practice, the corrections are included in ρ_b and κ_b, as discussed before.

For 3 fermion families the total widths are predicted to be

$$\Gamma_Z \approx 2.496 \pm 0.001\ \mathrm{GeV}\ \ , \tag{10.36}$$

$$\Gamma_W \approx 2.093 \pm 0.002\ \mathrm{GeV}\ \ . \tag{10.37}$$

We have assumed $\alpha_s = 0.120$. An uncertainty in α_s of ±0.003 introduces an additional uncertainty of 0.1% in the hadronic widths, corresponding to ±1.6 MeV in Γ_Z. These predictions are to be compared with the experimental results $\Gamma_Z = 2.4948 \pm 0.0025$ GeV and $\Gamma_W = 2.062 \pm 0.059$ GeV.

10.5. Experimental results

Table 10.3: Principal LEP and other recent observables, compared with the Standard Model predictions for $M_Z = 91.1867 \pm 0.0020$ GeV, $M_H = M_Z$, and the global best fit values $m_t = 173 \pm 4$ GeV, $\alpha_s = 0.1214 \pm 0.0031$, and $\widehat{\alpha}(M_Z)^{-1} = 127.90 \pm 0.07$. The LEP averages of the ALEPH, DELPHI, L3, and OPAL results include common systematic errors and correlations [57]. $\overline{s}_\ell^2(A_{FB}^{(0,q)})$ is the effective angle extracted from the hadronic charge asymmetry. The values of $\Gamma(\ell^+\ell^-)$, Γ(had), and Γ(inv) are not independent of Γ_Z, R_ℓ, and σ_{had}. The first M_W value is from CDF, UA2, and DØ [71] while the second includes the measurements at LEP [57]. M_W and M_Z are correlated, but the effect is negligible due to the tiny M_Z error. The four values of A_ℓ are (i) from A_{LR} for hadronic final states [59]; (ii) the combined value from SLD including leptonic asymmetries; (iii) from the total τ polarization; and (iv) from the angular distribution of the τ polarization. The two values of s_W^2 from deep-inelastic scattering are from CCFR [36] and the global average, respectively. Similarly, the $g_{V,A}^{\nu e}$ are from CHARM II [41] and the world average. The second errors in Q_W are theoretical [48,49]. Older low-energy results are not listed but are included in the fits. In the Standard Model predictions, the uncertainty is from M_Z, m_t, $\Delta\alpha(M_Z)$ and α_s. In parentheses we show the shift in the predictions when M_H is changed to 300 GeV which is its 90% CL upper limit. The errors in Γ_Z, Γ(had), R_ℓ, and σ_{had} are completely dominated by the uncertainty in α_s.

Quantity	Value	Standard Model
m_t [GeV]	175 ± 5	$173 \pm 4\ (+5)$
M_W [GeV]	80.405 ± 0.089	$80.377 \pm 0.023\ (-0.036)$
	80.427 ± 0.075	
M_Z [GeV]	91.1867 ± 0.0020	$91.1867 \pm 0.0020\ (+0.0001)$
Γ_Z [GeV]	2.4948 ± 0.0025	$2.4968 \pm 0.0017\ (-0.0007)$
Γ(had) [GeV]	1.7432 ± 0.0023	$1.7433 \pm 0.0016\ (-0.0005)$
Γ(inv) [MeV]	500.1 ± 1.8	$501.7 \pm 0.2\ (-0.1)$
$\Gamma(\ell^+\ell^-)$ [MeV]	83.91 ± 0.10	$84.00 \pm 0.03\ (-0.04)$
σ_{had} [nb]	41.486 ± 0.053	$41.469 \pm 0.016\ (-0.005)$
R_ℓ	20.775 ± 0.027	$20.754 \pm 0.020\ (+0.003)$
R_b	0.2170 ± 0.0009	$0.2158 \pm 0.0001\ (-0.0002)$
R_c	0.1734 ± 0.0048	$0.1723 \pm 0.0001\ (+0.0001)$
$A_{FB}^{(0,\ell)}$	0.0171 ± 0.0010	$0.0162 \pm 0.0003\ (-0.0004)$
$A_{FB}^{(0,b)}$	0.0984 ± 0.0024	$0.1030 \pm 0.0009\ (-0.0013)$
$A_{FB}^{(0,c)}$	0.0741 ± 0.0048	$0.0736 \pm 0.0007\ (-0.0010)$
$A_{FB}^{(0,s)}$	0.118 ± 0.018	$0.1031 \pm 0.0009\ (-0.0013)$
$\overline{s}_\ell^2(A_{FB}^{(0,q)})$	0.2322 ± 0.0010	$0.2315 \pm 0.0002\ (+0.0002)$
A_ℓ	0.1550 ± 0.0034	$0.1469 \pm 0.0013\ (-0.0018)$
	0.1547 ± 0.0032	
	0.1411 ± 0.0064	
	0.1399 ± 0.0073	
A_b	0.900 ± 0.050	$0.9347 \pm 0.0001\ (-0.0002)$
A_c	0.650 ± 0.058	$0.6678 \pm 0.0006\ (-0.0008)$
$s_W^2(\nu\mathrm{N})$	0.2236 ± 0.0041	$0.2230 \pm 0.0004\ (+0.0007)$
	0.2260 ± 0.0039	
$g_V^{\nu e}$	-0.035 ± 0.017	$-0.0395 \pm 0.0005\ (+0.0002)$
	-0.041 ± 0.015	
$g_A^{\nu e}$	-0.503 ± 0.017	$-0.5064 \pm 0.0002\ (+0.0002)$
	-0.507 ± 0.014	
Q_W(Cs)	$-72.41 \pm 0.25 \pm 0.80$	$-73.12 \pm 0.06\ (+0.01)$
Q_W(Tl)	$-114.8 \pm 1.2 \pm 3.4$	-116.7 ± 0.1

The values of the principal Z pole observables are listed in Table 10.3, along with the Standard Model predictions for $M_Z = 91.1867 \pm 0.0020$, $m_t = 173 \pm 4$ GeV, $M_H = M_Z$ and $\alpha_s = 0.1214 \pm 0.0031$. Note, that the values of the Z pole observables (as well as M_W) differ from those in the Particle Listings because they include recent preliminary results [57,58,59,71]. The values and predictions of M_W [57,71], the Q_W for cesium [44] and thallium [45], and recent results from deep inelastic [32–36] and $\nu_\mu e$ scattering [39–41] are also listed. The agreement is excellent. Even the largest discrepancies, A^0_{LR}, $A^{(0,b)}_{FB}$, and $A^{(0,\tau)}_{FB}$, deviate by only 2.4 σ, 1.9 σ and 1.7 σ, respectively.

Other observables like $R_b = \Gamma(b\bar{b})/\Gamma(\text{had})$ and $R_c = \Gamma(c\bar{c})/\Gamma(\text{had})$ which showed significant deviations in the past, are now in perfect (R_c) or at least better agreement. In particular, R_b whose measured value deviated as much as 3.7 σ from the Standard Model prediction is now only 1.3 σ high. Many types of new physics could contribute to R_b (the implications of this possibility for the value of $\alpha_s(M_Z)$ extracted from the fits are discussed below) and A_b and as a consequence to $A^{(0,b)}_{FB} = \frac{3}{4} A_e A_b$. Indeed, A_b can be extracted from $A^{(0,b)}_{FB}$ when A_e is taken from leptonic asymmetries (using lepton universality), and combined with the measurement at the SLC. The result, $A_b = 0.877 \pm 0.023$, is 2.5 σ below the Standard Model prediction. (Alternatively, one can use $A_\ell = 0.1469 \pm 0.0013$ from the global fit and obtain $A_b = 0.894 \pm 0.021$ which is 1.9 σ low.) However, this deviation of about 6% cannot arise from new physics radiative corrections since a 30% correction to $\widehat{\kappa}_b$ would be necessary to account for the central value of A_b. Only a new type of physics which couples at the tree level preferentially to the third generation, and which does not contradict R_b (including the off-peak R_b measurements by DELPHI [72]), can conceivably account for a low A_b [73].

The left-right asymmetry, $A^0_{LR} = 0.1550 \pm 0.0034$ [59], based on all hadronic data from 1992–1996 has moved closer to the Standard Model expectation of 0.1469 ± 0.0013 than previous values. However, because of the smaller error A^0_{LR} is still 2.4 σ above the Standard Model prediction. There is also an experimental difference of $\sim 1.9\ \sigma$ between the SLD value of $A_\ell(\text{SLD}) = 0.1547 \pm 00032$ from all A_{LR} and $A^{FB}_{LR}(\ell)$ data on one hand, and the LEP value $A_\ell(\text{LEP}) = 0.1461 \pm 0.0033$ obtained from $A^{(0,\ell)}_{FB}$, $A_e(\mathcal{P}_\tau)$, $A_\tau(\mathcal{P}_\tau)$ on the other hand, in both cases assuming lepton-family universality.

Despite these discrepancies the χ^2 value of the fit for the Standard Model is excellent. It is 25 for 30 d.o.f. when fitting to the independent observables in Table 10.3, and 181 for 209 d.o.f. when the older neutral current observables are included. The probability of a larger χ^2 is 0.73 and 0.92 for the two cases, respectively. (The low χ^2 for the older data is likely due to overly conservative estimates of systematic errors.)

With the latest value of $A^{(0,\tau)}_{FB}$ the data is now in reasonable agreement with lepton-family universality, which will be assumed. The observables in Table 10.3 (including correlations on the LEP lineshape and LEP/SLD heavy flavor observables), as well as all low-energy neutral-current data [16,17], are used in the global fits described below. The parameter $\sin^2\theta_W$ can be determined from Z pole observables, M_W, and from a variety of neutral-current processes spanning a very wide Q^2 range. The results [16], shown in Table 10.4, are in impressive agreement with each other, indicating the quantitative success of the Standard Model. The one discrepancy is the value $\widehat{s}^2_Z = 0.23023 \pm 0.00043$ from $A_\ell(\text{SLD})$ which is 2.3 σ below the value 0.23124 ± 0.00017 from the global fit to all data and 2.6 σ below the value 0.23144 ± 0.00019 obtained from all data other than $A_\ell(\text{SLD})$.

The data allow a simultaneous determination of $\sin^2\theta_W$, m_t, and the strong coupling $\alpha_s(M_Z)$. The latter is determined mainly from R_ℓ, Γ_Z, and σ_{had}, and is only weakly correlated with the other variables. The global fit to all data, including the CDF/DØ value, $m_t = 175 \pm 5$ GeV, yields

$$\begin{aligned} \widehat{s}^2_Z &= 0.23124 \pm 0.00017\ (+0.00024)\ , \\ m_t &= 173 \pm 4\ (+5)\ \text{GeV}\ , \\ \alpha_s(M_Z) &= 0.1214 \pm 0.0031\ (+0.0018)\ , \\ M_H &= M_Z\ . \end{aligned} \tag{10.38}$$

In parentheses we show the effect of changing M_H to 300 GeV which is the conservative 90% CL upper limit (see below). In all fits, the errors include full statistical, systematic, and theoretical uncertainties. The $\widehat{s}^2_Z$ error reflects the error on $\bar{s}^2_f \sim \pm 0.00023$ from the Z pole asymmetries. In the on-shell scheme one has $s^2_W = 0.22304 \pm 0.00044$, the larger error due to the stronger sensitivity to m_t. The extracted value of α_s is based on a formula with negligible theoretical uncertainty (± 0.0005 in α_s) if one assumes the exact validity of the Standard Model. It is in excellent agreement with other precise values [74], such as 0.122 ± 0.005 from τ decays, 0.121 ± 0.005 from jet-event shapes in e^+e^- annihilation, and the very recent result [75], 0.119 ± 0.002 (exp) ± 0.004 (scale), from deep-inelastic scattering. It is slightly higher than the values from lattice calculations of the $b\bar{b}$ (0.1174 ± 0.0024 [76]) and $c\bar{c}$ (0.116 ± 0.003 [77]) spectra, and from decays of heavy quarkonia (0.112 ± 0.006 [74]). For more details, see our Section 9 on "Quantum Chromodynamics" in this *Review*. The average $\alpha_s(M_Z)$ obtained from Section 9 when ignoring the precision measurements discussed in this Section is 0.1178 ± 0.0023. We use this value as an external constraint for the second fit in Table 10.5. The resulting value,

$$\alpha_s = 0.1191 \pm 0.0018\ (+0.0006)\ , \tag{10.39}$$

can be regarded as the present world average.

Table 10.4: Values obtained for s^2_W (on-shell) and $\widehat{s}^2_Z(\overline{\text{MS}})$ from various reactions assuming the global best fit values (for $M_H = M_Z$) $m_t = 173 \pm 4$ GeV and $\alpha_s = 0.1214 \pm 0.0031$.

Reaction	s^2_W	$\widehat{s}^2_Z$
M_Z	0.2231 ± 0.0005	0.2313 ± 0.0002
M_W	0.2228 ± 0.0006	0.2310 ± 0.0005
Γ_Z/M^3_Z, R, $\sigma_{\text{had}} M^2_Z$	0.2235 ± 0.0011	0.2316 ± 0.0011
$A^{(0,\ell)}_{FB}$	0.2225 ± 0.0007	0.2307 ± 0.0006
LEP asymmetries	0.2235 ± 0.0004	0.2317 ± 0.0003
A^0_{LR}	0.2220 ± 0.0005	0.2302 ± 0.0004
$\overline{A}_b, \overline{A}_c$	0.230 ± 0.016	0.239 ± 0.016
Deep inelastic (isocalar)	0.226 ± 0.004	0.234 ± 0.004
$\nu_\mu(\overline{\nu}_\mu)p \rightarrow \nu_\mu(\overline{\nu}_\mu)p$	0.203 ± 0.032	0.211 ± 0.032
$\nu_\mu(\overline{\nu}_\mu)e \rightarrow \nu_\mu(\overline{\nu}_\mu)e$	0.221 ± 0.008	0.229 ± 0.008
atomic parity violation	0.220 ± 0.003	0.228 ± 0.003
SLAC eD	0.213 ± 0.019	0.222 ± 0.018
All data	0.2230 ± 0.0004	0.23124 ± 0.00017

The value of R_b is 1.3 σ above the Standard Model expectation. If this is not just a fluctuation but is due to a new physics contribution to the $Z \rightarrow b\bar{b}$ vertex (many types would couple preferentially to the third family), the value of $\alpha_s(M_Z)$ extracted from the hadronic Z width would be reduced [17]. Allowing for this possibility one obtains $\alpha_s(M_Z) = 0.1166 \pm 0.0048\ (+0.0007)$. Similar remarks apply in principle for R_c and the other quark and lepton flavors, and one should keep in mind that the Z lineshape value of α_s is very sensitive to many types of new physics.

The data indicate a preference for a small Higgs mass. There is a strong correlation between the quadratic m_t and logarithmic M_H terms in $\widehat{\rho}$ in all of the indirect data except for the $Z \rightarrow b\bar{b}$ vertex. Therefore, observables (other than R_b) which favor m_t values higher than the Tevatron range favor lower values of M_H. This effect is enhanced by R_b, which has little direct M_H dependence but favors the lower end of the Tevatron m_t range. M_W has additional M_H dependence through $\Delta\widehat{r}_W$ which is not coupled to m^2_t effects. The strongest individual pulls towards smaller M_H are from M_W, A^0_{LR}, and $A^{(0,\ell)}_{FB}$ (when combined with M_Z), as well as R_b. The difference in χ^2 for the global fit is $\Delta\chi^2 = \chi^2(M_H = 1000\text{ GeV}) - \chi^2(M_H = 77\text{ GeV}) = 16.6$. Hence, the data favor a small value of M_H, as in supersymmetric extensions of the Standard Model, and m_t on the lower side of the Tevatron range. If one allows M_H as a free fit parameter and does not include any constraints from direct Higgs searches, one obtains $M_H = 69^{+85}_{-43}$ GeV, *i.e.*, the central value below the direct lower bound, $M_H \geq 77$ GeV (95% CL) [78]. Including the results of the direct searches as an extra contribution to the likelihood function drives the best fit value to the present kinematic reach ($M_H \sim 83$ GeV), and we obtain the upper limit $M_H < 236$ (287) GeV at 90 (95)% CL. The extraction of M_H from the precision data depends strongly on the value used for $\alpha(M_Z)$. The value derived by Martin and Zeppenfeld [11] relying on the predictions of perturbative QCD down to smaller values of $\sqrt{s}$ is higher and has a smaller stated error. Using this value would give a best fit at $M_H = 140$ GeV, and an upper limit $M_H < 300$ (361) GeV at 90 (95)% CL. Clearly, a consensus on the applicability of perturbative QCD in e^+e^- annihilation is highly desirable.

The most deviating observable, A_{LR}, has a strong impact on the Higgs mass limits as well [17,79]. The Introduction to this *Review* suggests an unbiased treatment of deviating observables r through the introduction of scale factors S_r. It is instructive to study the impact of this more conservative procedure on M_H. For the case of a fit to the Standard Model, we define

$$S_r = \max(\sqrt{\chi_r^2}, 1) \; , \qquad (10.40)$$

where χ_r^2 is the χ^2 contribution of observable r to a global fit in which M_H is allowed as a free fit parameter (with no direct constraints included). We then repeat the fit with all errors multiplied by S_r, and proceed iteratively until the procedure has converged. This way we obtain

$$S_{A^0_{LR}} = 2.76, \qquad S_{A^{(0,b)}_{FB}} = 2.05, \qquad S_{A^{(0,\tau)}_{FB}} = 1.83,$$

$$S_{A^{FB}_{LR}(\tau)} = 1.45, \qquad S_{A^{FB}_{LR}(\mu)} = 1.34, \qquad S_{R_b} = 1.33,$$

as well as $S_{A_e(\mathcal{P}_\tau)} = 1.02$, and $S_r = 1$ for all other observables. The result of the global fit is

$$\begin{aligned} \widehat{s}^2_Z &= 0.23141 \pm 0.00031 \; , \\ m_t &= 174 \pm 5 \text{ GeV} \; , \\ \alpha_s(M_Z) &= 0.1222 \pm 0.0034 \; , \\ M_H &= 122^{+134}_{-77} \text{ GeV} \; , \end{aligned} \qquad (10.41)$$

where the larger errors compared to Eq. (10.38) are from M_H rather than the S_r. Since the central value of M_H is much larger than the present direct lower bound, and $\log(M_H)$ is approximately normal distributed, it is justified to include the error due to M_H (with all correlations properly taken into account) in a Gaussian way in the uncertainties of the other parameters. For comparison with other fits we also list the results for fixed M_H in Table 10.5. Including the direct constraint we obtain an upper limit $M_H < 329$ (408) GeV at 90 (95)% CL, which is higher by $\mathcal{O}(100$ GeV) than the one without scale factors. It is in good agreement with the bound we obtained above by switching to the higher $\alpha(M_Z)$. Indeed, both analyses decrease the impact of A_{LR} on the Higgs mass limit.

A few comments are in order: (i) The procedure used here is not unambiguous. It depends on whether results from different experiments (*e.g.*, the various experimental groups at LEP or the Tevatron) are combined or used as individual pieces of input. We use combined result, primarily in order to avoid insurmountable complications with cross correlations between different experimental groups on top of the correlations between the observables. Even the result on a single observable quoted by an individual group, is in general a combination of various channels, with different types of systematic errors (which are the prime reason for the introduction of scale factors in the first place). Thus, ideally, one would prefer to define the S_r at this level. In practice, however, this is virtually impossible to achieve. In the case of M_W we use the individual determinations, since they are uncorrelated and are based on entirely different processes. (ii) None of the definitions of scale factors in the Introduction to this *Review* is directly applicable to our case. However, we have tried to work as closely as possible in spirit to the definitions given there. One major difference is that central values of fit parameters (in particular of M_H) change upon introducing S_r; on the other hand, central values of measurements remain unchanged. (iii) The procedure used here relies on the validity of the Standard Model, since in the presence of new physics, some discrepancies will be shifted into new physics parameters. When fits to new types of physics are to be compared to Standard Model fits as is done in Section 10.5 one has to refrain from using scale factors.

One can also carry out a fit to the indirect data alone, *i.e.*, without including the value $m_t = 175 \pm 5$ GeV observed directly by CDF and DØ. (The indirect prediction is for the $\overline{\text{MS}}$ mass which is in the end converted to the pole mass using an BLM optimized [80] version of the two-loop perturbative QCD formula [81]; this should correspond approximately to the kinematic mass extracted from the collider events.) One obtains $m_t = 170 \pm 7$ (+14) GeV, with little change in the $\sin^2\theta_W$ and α_s values, in remarkable agreement with the direct CDF/DØ value. The results of fits to various combinations of the data are shown in Table 10.5 and the relation between $\widehat{s}^2_Z$ and m_t for various observables in Fig. 10.1.

Table 10.5: Values of $\widehat{s}^2_Z$ and s^2_W (in parentheses), α_s, and m_t for various combinations of observables. The central values and uncertainties are for $M_H = M_Z$ while the third numbers show the shift (positive unless specified) from changing M_H to 300 GeV.

Data	$\widehat{s}^2_Z$ (s^2_W)	α_s (M_Z)	m_t [GeV]
All indirect + m_t	0.23124(17)(24) (0.2230±0.0004 (+0.0007))	0.1214(31)(18)	173(4)(5)
All indirect + $m_t + \alpha_s$	0.23121(17)(22) (0.2230±0.0004 (+0.0007))	0.1191(18)(6)	173(4)(5)
All indirect + $m_t + S_r$	0.23133(20)(32) (0.2232±0.0005 (+0.0008))	0.1218(31)(21)	173(4)(5)
All indirect	0.23129(19)(11) (0.2234±0.0007 (−0.0002))	0.1216(31)(14)	170(7)(14)
Z pole	0.23135(21)(10) (0.2236±0.0008 (−0.0003))	0.1218(31)(13)	168(8)(14)
LEP 1	0.23170(24)(13) (0.2247±0.0009 (−0.0002))	0.1232(31)(14)	160(8)(14)
SLD + M_Z	0.23023(43) (0.2192±0.0017 (−0.0008))	0.1200 (fixed)	203(13)(17)
$A^{(0,b)}_{FB}$ + M_Z	0.23209(45) (0.2261±0.0018 (−0.0009))	0.1200 (fixed)	147(17)(21)
M_W + M_Z	0.23101(43)(22) (0.2221±0.0015)	0.1200 (fixed)	181(12)(12)

Using $\alpha(M_Z)$ and $\widehat{s}^2_Z$ as inputs, one can predict $\alpha_s(M_Z)$ assuming grand unification. One predicts [82] $\alpha_s(M_Z) = 0.130 \pm 0.001 \pm 0.01$ for the simplest theories based on the minimal supersymmetric extension of the Standard Model, where the first (second) uncertainty is from the inputs (thresholds). This is consistent with the experimental $\alpha_s(M_Z) = 0.1216 \pm 0.0031 \pm 0.0003$ from the Z lineshape (with the second error corresponding to $M_H < 150$ GeV, as is appropriate to the lower M_H range appropriate for supersymmetry) and with the world average 0.119 ± 0.002. Nonsupersymmetric unified theories predict the low value $\alpha_s(M_Z) = 0.073 \pm 0.001 \pm 0.001$. See also the note on "Low-Energy Supersymmetry" in the Particle Listings.

One can also determine the radiative correction parameters Δr: including the CDF and DØ data, one obtains $\Delta r = 0.0355 \pm$

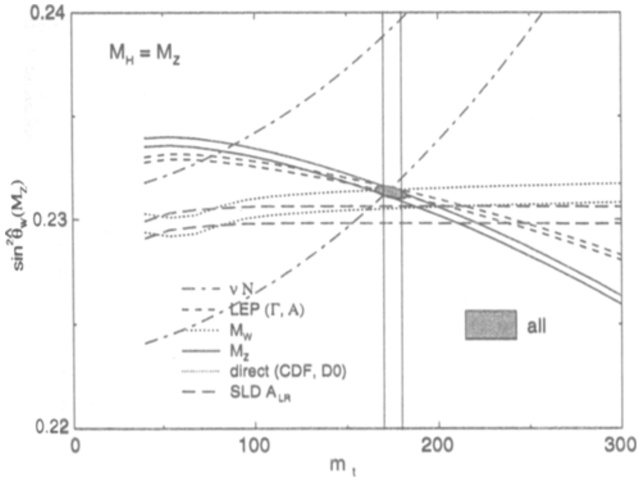

Figure 10.1: One-standard-deviation uncertainties in $\sin^2\hat{\theta}_W$ as a function of m_t, the direct CDF and DØ range 175 ± 5 GeV, and the 90% CL region in $\sin^2\hat{\theta}_W - m_t$ allowed by all data, assuming $M_H = M_Z$.

0.0014 (+0.0021) and $\Delta\hat{r}_W = 0.0697 \pm 0.0005\ (+0.0001)$, in excellent agreement with the predictions 0.0349 ± 0.0020 and 0.0698 ± 0.0007. M_W measurements [57,71] (when combined with M_Z) are equivalent to measurements of $\Delta r = 0.0325 \pm 0.0045$.

Table 10.6: Values of the model-independent neutral-current parameters, compared with the Standard Model predictions for $M_Z = 91.1867 \pm 0.0020$ GeV, $M_H = M_Z$, and the global best fit values $m_t = 173 \pm 4$ GeV, $\alpha_s = 0.1214 \pm 0.0031$, and $\hat{\alpha}(M_Z)^{-1} = 127.90 \pm 0.07$. There is a second $g_{V,A}^{\nu e}$ solution, given approximately by $g_V^{\nu e} \leftrightarrow g_A^{\nu e}$, which is eliminated by e^+e^- data under the assumption that the neutral current is dominated by the exchange of a single Z. θ_i, $i = L$ or R, is defined as $\tan^{-1}[\epsilon_i(u)/\epsilon_i(d)]$.

Quantity	Experimental Value	Standard Model Prediction		Correlation
$\epsilon_L(u)$	$0.328\ \pm 0.016$	0.3461 ± 0.0002		non-Gaussian
$\epsilon_L(d)$	$-0.440\ \pm 0.011$	-0.4292 ± 0.0002		
$\epsilon_R(u)$	$-0.179\ \pm 0.013$	-0.1548 ± 0.0001		
$\epsilon_R(d)$	$-0.027\ {}^{+0.077}_{-0.048}$	0.0775 ± 0.0001		
g_L^2	0.3009 ± 0.0028	0.3040 ± 0.0003		small
g_R^2	0.0328 ± 0.0030	0.0300		
θ_L	$2.50\ \pm 0.035$	2.4629 ± 0.0001		
θ_R	$4.56\ {}^{+0.42}_{-0.27}$	5.1765		
$g_V^{\nu e}$	$-0.041\ \pm 0.015$	-0.0395 ± 0.0005		-0.04
$g_A^{\nu e}$	$-0.507\ \pm 0.014$	-0.5064 ± 0.0002		
C_{1u}	$-0.216\ \pm 0.046$	-0.1885 ± 0.0003	-0.997	-0.78
C_{1d}	$0.361\ \pm 0.041$	0.3412 ± 0.0002		0.78
$C_{2u} - \frac{1}{2}C_{2d}$	$-0.03\ \pm 0.12$	-0.0488 ± 0.0008		

Most of the parameters relevant to ν-hadron, νe, e-hadron, and e^+e^- processes are determined uniquely and precisely from the data in "model independent" fits (*i.e.*, fits which allow for an arbitrary electroweak gauge theory). The values for the parameters defined in Eqs. (10.12)–(10.14) are given in Table 10.6 along with the predictions of the Standard Model. The agreement is excellent. The low-energy e^+e^- results are difficult to present in a model-independent way because Z propagator effects are non-negligible at TRISTAN, PETRA, and PEP energies. However, assuming e-μ-τ universality, the lepton asymmetries imply [55] $4(g_A^e)^2 = 0.99 \pm 0.05$, in good agreement with the Standard Model prediction $\simeq 1$.

The results presented here are generally in reasonable agreement with the ones obtained by the LEP Electroweak Working Group [57]. We obtain slightly higher values for α_s and significantly lower best fit values for M_H. We could trace the differences to be due to (i) the inclusion of recent higher order radiative corrections, in particular, $\mathcal{O}(\alpha^2 m_t^2)$ [26] and $\mathcal{O}(\alpha\alpha_s)$ vertex [68] corrections, as well as the leading $\mathcal{O}(\alpha_s^4)$ contribution to hadronic Z decays; (ii) the use of a slightly higher value of $\alpha(M_Z)$ [9]; (iii) a more complete set of low energy data (which is not very important for Standard Model fits, but is for physics beyond the Standard Model); and (iv) scheme dependences. Taking into account these differences, the agreement is excellent.

10.6. Constraints on new physics

The Z pole, W mass, and neutral-current data can be used to search for and set limits on deviations from the Standard Model. In particular, the combination of these indirect data with the direct CDF and DØ value for m_t allows stringent limits on new physics. We will mainly discuss the effects of exotic particles (with heavy masses $M_{\rm new} \gg M_Z$ in an expansion in $M_Z/M_{\rm new}$) on the gauge boson self-energies. (Brief remarks are made on new physics which is not of this type.) Most of the effects on precision measurements can be described by three gauge self-energy parameters S, T, and U. We will define these, as well as related parameters, such as ρ_0, ϵ_i, and $\hat{\epsilon}_i$, to arise from new physics only. *I.e.*, they are equal to zero ($\rho_0 = 1$) exactly in the Standard Model, and do not include any contributions from m_t or M_H, which are treated seperately. Our treatment differs from most of the original papers. We also allow a $Zb\bar{b}$ vertex correction parameter γ_b.

Many extensions of the Standard Model are described by the ρ_0 parameter:

$$\rho_0 \equiv M_W^2/(M_Z^2\,\hat{c}_Z^2\,\hat{\rho})\ , \tag{10.42}$$

which describes new sources of SU(2) breaking that cannot be accounted for by Higgs doublets or m_t effects. In the presence of $\rho_0 \neq 1$, Eq. (10.42) generalizes Eq. (10.9*b*), while Eq. (10.9*a*) remains unchanged. Provided that the new physics which yields $\rho_0 \neq 1$ is a small perturbation which does not significantly affect the radiative corrections, ρ_0 can be regarded as a phenomenological parameter which multiplies G_F in Eqs. (10.12)–(10.14), (10.28), and Γ_Z in Eq. (10.35). There is now enough data to determine ρ_0, $\sin^2\theta_W$, m_t, and α_s simultaneously. In particular, the direct CDF and DØ events and R_b yield m_t independent of ρ_0, the asymmetries yield $\hat{s}_Z^2$, R_ℓ gives α_s, and M_Z and the widths constrain ρ_0. From the global fit,

$$\rho_0 = 0.9998 \pm 0.0008\ (+0.0014)\ , \tag{10.43}$$
$$\hat{s}_Z^2 = 0.23126 \pm 0.00019\ (+0.00010)\ , \tag{10.44}$$
$$\alpha_s = 0.1219 \pm 0.0034\ (-0.0009)\ , \tag{10.45}$$
$$m_t = 174 \pm 5\ \text{ GeV}\ , \tag{10.46}$$

where the central values are for $M_H = M_Z$ and in parentheses we show the effect of changing M_H to 300 GeV. (As in the case $\rho_0 = 1$, the best fit value for M_H is below its direct lower limit.) The allowed regions in the $\rho_0 - \hat{s}_Z^2$ plane are shown in Fig. 10.2.

The result in Eq. (10.43) is in remarkable agreement with the Standard Model expectation, $\rho_0 = 1$. It can be used to constrain higher-dimensional Higgs representations to have vacuum expectation values of less than a few percent of those of the doublets. Indeed, the relation between M_W and M_Z is modified if there are Higgs multiplets with weak isospin > 1/2 with significant vacuum expectation values. In order to calculate to higher orders in such theories one must define a set of four fundamental renormalized parameters which one may conveniently choose to be α, G_F, M_Z, and M_W, since M_W and M_Z are directly measurable. Then $\hat{s}_Z^2$ and ρ_0 can be considered dependent parameters.

Eq. (10.43) can also be used to constrain other types of new physics. For example, nondegenerate multiplets of heavy fermions or scalars break the vector part of weak SU(2) and lead to a decrease in the value of M_Z/M_W. A nondegenerate SU(2) doublet $\binom{f_1}{f_2}$ yields a

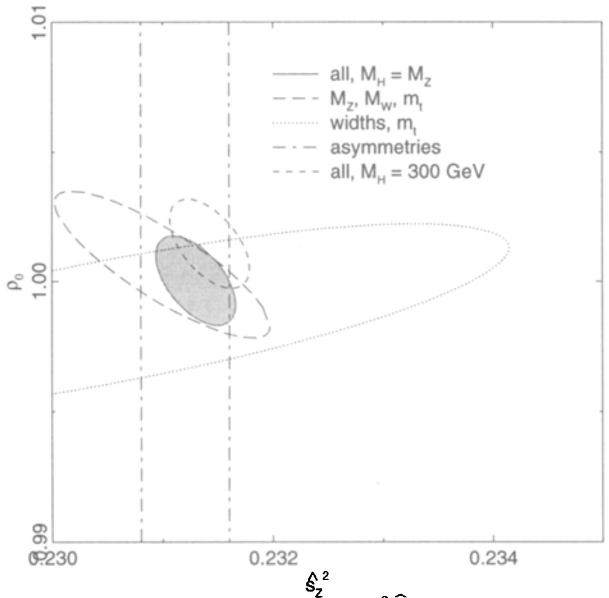

Figure 10.2: The allowed regions in $\sin^2\hat{\theta}_W - \rho_0$ at 90% CL. m_t is a free parameter and $M_H = M_Z$ is assumed except for the dashed contour for all data which is for M_H = 300 GeV. The horizontal (width) band uses the experimental value of M_Z in Eq. (10.35).

positive contribution to ρ_t of [83]

$$\frac{CG_F}{8\sqrt{2}\pi^2}\Delta m^2 , \tag{10.47}$$

where

$$\Delta m^2 \equiv m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\frac{m_1}{m_2} \geq (m_1 - m_2)^2 , \tag{10.48}$$

and $C = 1$ (3) for color singlets (triplets). Thus, in the presence of such multiplets, one has

$$\frac{3G_F}{8\sqrt{2}\pi^2}\sum_i \frac{C_i}{3}\,\Delta m_i^2 = \rho_0 - 1 , \tag{10.49}$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in supersymmetry (in the absence of $L - R$ mixing). This implies

$$\sum_i \frac{C_i}{3}\,\Delta m_i^2 < (49\ \text{GeV})^2 \ \text{and}\ (83\ \text{GeV})^2 \tag{10.50}$$

for $M_H = M_Z$ and 300 GeV, respectively, at 90% CL.

Nondegenerate multiplets usually imply $\rho_0 > 1$. Similarly, heavy Z' bosons decrease the prediction for M_Z due to mixing and generally lead to $\rho_0 > 1$ [84]. On the other hand, additional Higgs doublets which participate in spontaneous symmetry breaking [85], heavy lepton doublets involving Majorana neutrinos [86], and the vacuum expectation values of Higgs triplets or higher-dimensional representations can contribute to ρ_0 with either sign. Allowing for the presence of heavy degenerate chiral multiplets (the S parameter, to be discussed below) affects the determination of ρ_0 from the data, at present leading to a smaller value.

A number of authors [87–92] have considered the general effects on neutral current and Z and W pole observables of various types of heavy (*i.e.*, $M_{\text{new}} \gg M_Z$) physics which contribute to the W and Z self-energies but which do not have any direct coupling to the ordinary fermions. In addition to nondegenerate multiplets, which break the vector part of weak SU(2), these include heavy degenerate multiplets of chiral fermions which break the axial generators. The effects of one degenerate chiral doublet are small, but in technicolor theories there may be many chiral doublets and therefore significant effects [87].

Such effects can be described by just three parameters, S, T, and U at the (electroweak) one loop level. (Three additional parameters are needed if the new physics scale is comparable to M_Z [93].) T is proportional to the difference between the W and Z self-energies at $Q^2 = 0$ (*i.e.*, vector SU(2)-breaking), while S ($S + U$) is associated with the difference between the Z (W) self-energy at $Q^2 = M^2_{Z,W}$ and $Q^2 = 0$ (axial SU(2)-breaking). In the $\overline{\text{MS}}$ scheme [20]

$$\begin{aligned}
\alpha(M_Z)T &\equiv \frac{\Pi^{\text{new}}_{WW}(0)}{M_W^2} - \frac{\Pi^{\text{new}}_{ZZ}(0)}{M_Z^2} , \\
\frac{\alpha(M_Z)}{4\hat{s}^2_Z\hat{c}^2_Z}S &\equiv \frac{\Pi^{\text{new}}_{ZZ}(M_Z^2) - \Pi^{\text{new}}_{ZZ}(0)}{M_Z^2} , \\
\frac{\alpha(M_Z)}{4\hat{s}^2_Z}(S + U) &\equiv \frac{\Pi^{\text{new}}_{WW}(M_W^2) - \Pi^{\text{new}}_{WW}(0)}{M_W^2} ,
\end{aligned} \tag{10.51}$$

where Π^{new}_{WW} and Π^{new}_{ZZ} are, respectively, the contributions of the new physics to the W and Z self-energies. S, T, and U are defined with a factor of α removed, so that they are expected to be of order unity in the presence of new physics. They are related to other parameters ($\hat{\epsilon}_i$, h_i, S_i) defined in [20,88,89] by

$$\begin{aligned}
T &= h_V = \hat{\epsilon}_1/\alpha , \\
S &= h_{AZ} = S_Z = 4\hat{s}^2_Z\hat{\epsilon}_3/\alpha , \\
U &= h_{AW} - h_{AZ} = S_W - S_Z = -4\hat{s}^2_Z\hat{\epsilon}_2/\alpha .
\end{aligned} \tag{10.52}$$

A heavy nondegenerate multiplet of fermions or scalars contributes positively to T as

$$\rho_0 = \frac{1}{1 - \alpha T} \simeq 1 + \alpha T , \tag{10.53}$$

where ρ_0 is given in Eq. (10.49). The effects of nonstandard Higgs representations cannot be separated from heavy nondegenerate multiplets unless the new physics has other consequences, such as vertex corrections. Most of the original papers defined T to include the effects of loops only. However, we will redefine T to include all new sources of SU(2) breaking, including nonstandard Higgs, so that T and ρ_0 are equivalent by Eq. (10.53).

A multiplet of heavy degenerate chiral fermions yields

$$S = C\sum_i \Big(t_{3L}(i) - t_{3R}(i)\Big)^2/3\pi , \tag{10.54}$$

where $t_{3L,R}(i)$ is the third component of weak isospin of the left- (right-) handed component of fermion i and C is the number of colors. For example, a heavy degenerate ordinary or mirror family would contribute $2/3\pi$ to S. In technicolor models with QCD-like dynamics, one expects [87] $S \sim 0.45$ for an isodoublet of technifermions, assuming $N_{TC} = 4$ technicolors, while $S \sim 1.62$ for a full technigeneration with $N_{TC} = 4$; T is harder to estimate because it is model dependent. In these examples one has $S \geq 0$. However, the QCD-like models are excluded on other grounds (flavor-changing neutral currents, and too-light quarks and pseudo-Goldstone bosons [94]). In particular, these estimates do not apply to models of walking technicolor [94], for which S can be smaller or even negative [95]. Other situations in which $S < 0$, such as loops involving scalars or Majorana particles, are also possible [96]. Supersymmetric extensions of the Standard Model generally give very small effects [97]. Most simple types of new physics yield $U = 0$, although there are counter-examples, such as the effects of anomalous triple-gauge vertices [89].

The Standard Model expressions for observables are replaced by

$$\begin{aligned}
M_Z^2 &= M_{Z0}^2\frac{1 - \alpha T}{1 - G_F M_{Z0}^2 S/2\sqrt{2}\pi} , \\
M_W^2 &= M_{W0}^2\frac{1}{1 - G_F M_{W0}^2 (S + U)/2\sqrt{2}\pi} ,
\end{aligned} \tag{10.55}$$

where M_{Z0} and M_{W0} are the Standard Model expressions (as functions of m_t and M_H) in the $\overline{\rm MS}$ scheme. Furthermore,

$$\begin{aligned} \Gamma_Z &= \frac{1}{1-\alpha T} M_Z^3 \beta_Z \ , \\ \Gamma_W &= M_W^3 \beta_W \ , \\ A_i &= \frac{1}{1-\alpha T} A_{i0} \ , \end{aligned} \tag{10.56}$$

where β_Z and β_W are the Standard Model expressions for the reduced widths Γ_{Z0}/M_{Z0}^3 and Γ_{W0}/M_{W0}^3, M_Z and M_W are the physical masses, and A_i (A_{i0}) is a neutral current amplitude (in the Standard Model).

The $Z \to b\bar{b}$ vertex is sensitive to certain types of new physics which primarily couple to heavy families. It is useful to introduce an additional parameter γ_b by [98]

$$\Gamma(Z \to b\bar{b}) = \Gamma^0(Z \to b\bar{b})(1+\gamma_b) \ , \tag{10.57}$$

where Γ^0 is the Standard Model expression (or the expression modified by S, T, and U). Experimentally, R_b is 1.3 σ above the Standard Model expectations, favoring a positive γ_b. Extended technicolor interactions generally yield negative values of γ_b of a few percent [99], although it is possible to obtain a positive γ_b in models for which the extended technicolor group does not commute with the electroweak gauge group [100] or for which diagonal interactions related to the extended technicolor dominate [101]. Topcolor and topcolor-assisted technicolor models do not generally give a significant contribution to γ_b because the extended technicolor contribution to m_t is small [102]. Supersymmetry can yield (typically small) contributions of either sign [103,104].

The data allow a simultaneous determination of $\hat{s}_Z^2$ (*e.g.*, from the Z pole asymmetries), S (from M_Z), U (from M_W), T (*e.g.*, from the Z decay widths), α_s (from R_ℓ), m_t (from CDF and DØ), and γ_b (from R_b) with little correlation among the Standard Model parameters:

$$\begin{aligned} S &= -0.16 \pm 0.14\,(-0.10) \ , \\ T &= -0.21 \pm 0.16\,(+0.10) \ , \\ U &= 0.25 \pm 0.24\,(+0.01) \ , \\ \gamma_b &= 0.007 \pm 0.005 \ , \end{aligned} \tag{10.58}$$

and $\hat{s}_Z^2 = 0.23118 \pm 0.00023$, $\alpha_s = 0.1191 \pm 0.0051$, $m_t = 175 \pm 5$ GeV, where the uncertainties are from the inputs. The central values assume $M_H = M_Z$, and in parentheses we show the change for $M_H = 300$ GeV. The parameters in Eq. (10.58) which by definition are due to new physics only, are all consistent with the Standard Model values of zero near the 1σ level, although at present there is a slight tendency for negative S and T, and positive U and γ_b. With the latest value of R_b, the extracted $\alpha_s = 0.1191 \pm 0.0051$ is now in perfect agreement with other determinations, even in the presence of the large class of new physics allowed in this fit. Its error is slightly higher than in Eq. (10.38) for the Standard Model, but the central value is independent of M_H. Using Eq. (10.53) the value of ρ_0 corresponding to T is 0.9984 ± 0.0012 ($+0.0008$). The values of the $\hat{\epsilon}$ parameters defined in Eq. (10.52) are

$$\begin{aligned} \hat{\epsilon}_3 &= -0.0013 \pm 0.0012\,(-0.0009) \ , \\ \hat{\epsilon}_1 &= -0.0016 \pm 0.0012\,(+0.0008) \ , \\ \hat{\epsilon}_2 &= -0.0022 \pm 0.0021\,(-0.0001) \ . \end{aligned} \tag{10.59}$$

There is a strong correlation between γ_b and the predicted α_s (the correlation coefficient is -0.69), just as in the model with $S = T = U = 0$ [17]. For $\gamma_b = 0$ one obtains $\alpha_s = 0.1239 \pm 0.0037$, with little change in the other parameters. The largest correlation coefficient ($+0.73$) is between S and T. The allowed region in $S - T$ is shown in Fig. 10.3. From Eq. (10.58) one obtains $S < 0.03\,(0.08)$ and $T < 0.09\,(0.15)$ at 90(95)% CL for $M_H = M_Z$ (S) and 300 GeV (T). If one fixes $M_H = 600$ GeV and requires the constraint $S \geq 0$ (as is appropriate in QCD-like technicolor models) then $S < 0.12\,(0.15)$. Allowing arbitrary S, an extra generation of ordinary fermions is now excluded at the 99.2% CL. This is in agreement with a fit to the number of light neutrinos, $N_\nu = 2.993 \pm 0.011$. The favored value of S is problematic for simple technicolor models with many techni-doublets and QCD-like dynamics, as is the value of γ_b. Although S is consistent with zero, the electroweak asymmetries, especially the SLD left-right asymmetry, favor $S < 0$. The simplest origin of $S < 0$ would probably be an additional heavy Z' boson [84], which could mimic $S < 0$. Similarly, there is a slight indication of negative T, while, as discussed above, nondegenerate scalar or fermion multiplets generally predict $T > 0$.

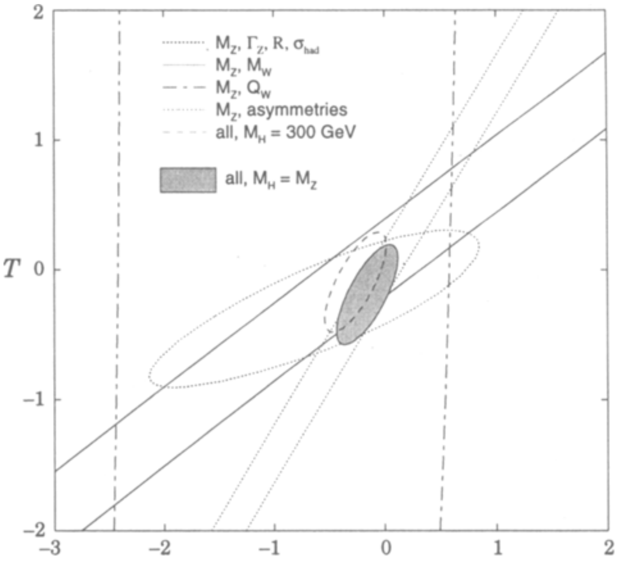

Figure 10.3: 90% CL limits on S and T from various inputs. S and T represent the contributions of new physics only. (Uncertainties from m_t are included in the errors.) The contours assume $M_H = M_Z$ except for the dashed contour for all data which is for $M_H = 300$ GeV. The fit to M_W and M_Z assumes $U = 0$, while U is arbitrary in the other fits.

There is no simple parametrization that is powerful enough to describe the effects of every type of new physics on every possible observable. The S, T, and U formalism describes many types of heavy physics which affect only the gauge self-energies, and it can be applied to all precision observables. However, new physics which couples directly to ordinary fermions, such as heavy Z' bosons [84] or mixing with exotic fermions [105] cannot be fully parametrized in the S, T, and U framework. It is convenient to treat these types of new physics by parametrizations that are specialized to that particular class of theories (*e.g.*, extra Z' bosons), or to consider specific models (which might contain, *e.g.*, Z' bosons and exotic fermions with correlated parameters). Constraints on various types of new physics are reviewed in [17,106,107]. Fits to models with technicolor, extended technicolor, and supersymmetry are described, respectively, in [100], [108], and [109]. An alternate formalism [110] defines parameters, ϵ_1, ϵ_2, ϵ_3, ϵ_b in terms of the specific observables M_W/M_Z, $\Gamma_{\ell\ell}$, $A_{FB}^{(0,\ell)}$, and R_b. The definitions coincide with those for $\hat{\epsilon}_i$ in Eqs. (10.51) and (10.52) for physics which affects gauge self-energies only, but the ϵ's now parametrize arbitrary types of new physics. However, the ϵ's are not related to other observables unless additional model-dependent assumptions are made. Another approach [111–113] parametrizes new physics in terms of gauge-invariant sets of operators. It is especially powerful in studying the effects of new physics on nonabelian gauge vertices. The most general approach introduces deviation vectors [106]. Each type of new physics defines a deviation vector, the components of which are the deviations of each observable from its Standard Model prediction, normalized to the experimental uncertainty. The length (direction) of the vector represents the strength (type) of new physics.

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11. THE CABIBBO-KOBAYASHI-MASKAWA MIXING MATRIX

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In the Standard Model with SU(2) × U(1) as the gauge group of electroweak interactions, both the quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these bases was defined for six quarks and given an explicit parametrization by Kobayashi and Maskawa [1] in 1973. It generalizes the four-quark case, where the matrix is parametrized by a single angle, the Cabibbo angle [2].

By convention, the mixing is often expressed in terms of a 3 × 3 unitary matrix V operating on the charge $-e/3$ quarks (d, s, and b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \qquad (11.1)$$

The values of individual matrix elements can in principle all be determined from weak decays of the relevant quarks, or, in some cases, from deep inelastic neutrino scattering. Using the constraints discussed below together with unitarity, and assuming only three generations, the 90% confidence limits on the magnitude of the elements of the complete matrix are:

$$\begin{pmatrix} 0.9745 \text{ to } 0.9760 & 0.217 \text{ to } 0.224 & 0.0018 \text{ to } 0.0045 \\ 0.217 \text{ to } 0.224 & 0.9737 \text{ to } 0.9753 & 0.036 \text{ to } 0.042 \\ 0.004 \text{ to } 0.013 & 0.035 \text{ to } 0.042 & 0.9991 \text{ to } 0.9994 \end{pmatrix} . \qquad (11.2)$$

The ranges shown are for the individual matrix elements. The constraints of unitarity connect different elements, so choosing a specific value for one element restricts the range of others.

There are several parametrizations of the Cabibbo-Kobayashi-Maskawa matrix. We advocate a "standard" parametrization [3] of V that utilizes angles θ_{12}, θ_{23}, θ_{13}, and a phase, δ_{13}:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \qquad (11.3)$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ for the "generation" labels $i, j = 1, 2, 3$. This has distinct advantages of interpretation, for the rotation angles are defined and labeled in a way which relate to the mixing of two specific generations and if one of these angles vanishes, so does the mixing between those two generations; in the limit $\theta_{23} = \theta_{13} = 0$ the third generation decouples, and the situation reduces to the usual Cabibbo mixing of the first two generations with θ_{12} identified with the Cabibbo angle [2]. The real angles θ_{12}, θ_{23}, θ_{13} can all be made to lie in the first quadrant by an appropriate redefinition of quark field phases.

The matrix elements in the first row and third column, which can be directly measured in decay processes, are all of a simple form, and as c_{13} is known to deviate from unity only in the sixth decimal place, $V_{ud} = c_{12}$, $V_{us} = s_{12}$, $V_{ub} = s_{13}\ e^{\delta_{13}}$, $V_{cb} = s_{23}$, and $V_{tb} = c_{23}$ to an excellent approximation. The phase δ_{13} lies in the range $0 \leq \delta_{13} < 2\pi$, with non-zero values generally breaking CP invariance for the weak interactions. The generalization to the n generation case contains $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases. The range of matrix elements in Eq. (11.2) corresponds to 90% CL limits on the sines of the angles of $s_{12} = 0.217$ to $0.222, s_{23} = 0.036$ to 0.042, and $s_{13} = 0.0018$ to 0.0044.

Kobayashi and Maskawa [1] originally chose a parametrization involving the four angles, θ_1, θ_2, θ_3, δ:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3+c_2s_3e^{i\delta} & c_1s_2s_3-c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \qquad (11.4)$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. In the limit $\theta_2 = \theta_3 = 0$, this reduces to the usual Cabibbo mixing with θ_1 identified (up to a sign) with the Cabibbo angle [2]. Several different forms of the Kobayashi-Maskawa parametrization are found in the literature. Since all these parametrizations are referred to as "the" Kobayashi-Maskawa form, some care about which one is being used is needed when the quadrant in which δ lies is under discussion.

A popular approximation that emphasizes the hierarchy in the size of the angles, $s_{12} \gg s_{23} \gg s_{13}$, is due to Wolfenstein [4], where one sets $\lambda \equiv s_{12}$, the sine of the Cabibbo angle, and then writes the other elements in terms of powers of λ:

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} . \qquad (11.5)$$

with A, ρ, and η real numbers that were intended to be of order unity. No physics can depend on which of the above parametrizations (or any other) is used as long as a single one is used consistently and care is taken to be sure that no other choice of phases is in conflict.

Our present knowledge of the matrix elements comes from the following sources:

(1) $|V_{ud}|$ - Analyses have been performed comparing nuclear beta decays that proceed through a vector current to muon decay. Radiative corrections are essential to extracting the value of the matrix element. They already include [5] effects of order $Z\alpha^2$, and most of the theoretical argument centers on the nuclear mismatch and structure-dependent radiative corrections [6,7]. New data have been obtained on superallowed $0^+ \to 0^+$ beta decays [8]. Taking the complete data set for nine decays, the values obtained in analyses by two groups are:

$$\begin{aligned} ft &= 3146.0 \pm 3.2 \quad \text{(Ref. 8)} \\ ft &= 3150.8 \pm 2.8 \quad \text{(Ref. 9)} . \end{aligned} \qquad (11.6)$$

Averaging these results (essentially for $|V_{ud}|^{-2}$), but keeping the same error bar, we obtain $|V_{ud}| = 0.9735 \pm 0.0005$. It has been argued [10] that the change in charge-symmetry-violation for quarks inside nucleons that are in nuclear matter results in a further increase of the ft value by 0.075 to 0.2%, leading to a systematic underestimate of $|V_{ud}|$. While more work needs to be done to clarify the structure-dependent effects, for now we add linearly a further 0.1 ± 0.1% to the ft values coming from nuclear decays, obtaining a value:

$$|V_{ud}| = 0.9740 \pm 0.0010 . \qquad (11.7)$$

(2) $|V_{us}|$ - Analysis of K_{e3} decays yields [11]

$$|V_{us}| = 0.2196 \pm 0.0023 . \qquad (11.8)$$

With isospin violation taken into account in K^+ and K^0 decays, the extracted values of $|V_{us}|$ are in agreement at the 1% level. A reanalysis [7] obtains essentially the same value, but quotes a somewhat smaller error which is only statistical. The analysis [12] of hyperon decay data has larger theoretical uncertainties because of first order SU(3) symmetry breaking effects in the axial-vector couplings. This has been redone incorporating second order SU(3) symmetry breaking corrections in models [13] applied to the WA2 data [14] to give a value of $|V_{us}| = 0.2176 \pm 0.0026$ with the "best-fit" model, which is consistent with Eq. (11.8). Since the values obtained in the models differ outside the errors and generally do not give good fits, we retain the value in Eq. (11.8) for $|V_{us}|$.

(3) $|V_{cd}|$ - The magnitude of $|V_{cd}|$ may be deduced from neutrino and antineutrino production of charm off valence d quarks. The dimuon production cross sections of the CDHS group [15] yield $\overline{B}_c\,|V_{cd}|^2 = 0.41 \pm 0.07 \times 10^{-2}$, where $\overline{B}_c$ is the semileptonic branching fraction of the charmed hadrons produced. The corresponding value from a more recent Tevatron experiment [16], where a next-to-leading-order

QCD analysis has been carried out, is $0.534 \pm 0.021^{+0.025}_{-0.051} \times 10^{-2}$, where the last error is from the scale uncertainty. Assuming a similar scale error for the CDHS result and averaging these two results gives $0.49 \pm 0.05 \times 10^{-2}$. Supplementing this with data [17] on the mix of charmed particle species produced by neutrinos and PDG values for their semileptonic branching fractions to give [16] $\overline{B}_c = 0.099 \pm 0.012$, then yields

$$|V_{cd}| = 0.224 \pm 0.016 \qquad (11.9)$$

(4) $|V_{cs}|$ – Values of $|V_{cs}|$ from neutrino production of charm are dependent on assumptions about the strange quark density in the parton-sea. The most conservative assumption, that the strange-quark sea does not exceed the value corresponding to an $SU(3)$ symmetric sea, leads to a lower bound [15], $|V_{cs}| > 0.59$. It is more advantageous to proceed analogously to the method used for extracting $|V_{us}|$ from K_{e3} decay; namely, we compare the experimental value for the width of D_{e3} decay with the expression [18] that follows from the standard weak interaction amplitude:

$$\Gamma(D \to \overline{K} e^+ \nu_e) = |f_+^D(0)|^2 \, |V_{cs}|^2 \, (1.54 \times 10^{11} \text{ s}^{-1}) \; . \qquad (11.10)$$

Here $f_+^D(q^2)$, with $q = p_D - p_K$, is the form factor relevant to D_{e3} decay; its variation has been taken into account with the parametrization $f_+^D(t)/f_+^D(0) = M^2/(M^2 - t)$ and $M = 2.1$ GeV/c^2, a form and mass consistent with direct measurements [19]. Combining data on branching ratios for D_{e3} decays with accurate values for the D lifetimes [19] yields a value of $(0.818 \pm 0.041) \times 10^{11}$ s^{-1} for $\Gamma(D \to \overline{K} e^+ \nu_e)$. Therefore

$$|f_+^D(0)|^2 \, |V_{cs}|^2 = 0.531 \pm 0.027 \; . \qquad (11.11)$$

A very conservative assumption is that $|f_+^D(0)| < 1$, from which it follows that $|V_{cs}| > 0.62$. Calculations of the form factor either performed [20,21] directly at $q^2 = 0$, or done [22] at the maximum value of $q^2 = (m_D - m_K)^2$ and interpreted at $q^2 = 0$ using the measured q^2 dependence, gives the value $f_+^D(0) = 0.7 \pm 0.1$. It follows that

$$|V_{cs}| = 1.04 \pm 0.16 \; . \qquad (11.12)$$

The constraint of unitarity when there are only three generations gives a much tighter bound (see below).

(5) $|V_{cb}|$ – The heavy quark effective theory [24](HQET) provides a nearly model-independent treatment of B semileptonic decays to charmed mesons, assuming that both the b and c quarks are heavy enough for the theory to apply. From measurements of the exclusive decay $B \to \overline{D}^* \ell^+ \nu_\ell$, the value $|V_{cb}| = 0.0387 \pm 0.0021$ has been extracted [25] using corrections based on the HQET. Exclusive $B \to \overline{D} \ell^+ \nu_\ell$ decays give a consistent but less precise result. Analysis of inclusive decays, where the measured semileptonic bottom hadron partial width is assumed to be that of a b quark decaying through the usual $V - A$ interaction, depends on going from the quark to hadron level. This is also understood within the context of the HQET [26], and the results for $|V_{cb}|$ are again consistent with those from exclusive decays. Combining all these results [25]:

$$|V_{cb}| = 0.0395 \pm 0.0017 \; , \qquad (11.13)$$

which is now the third most accurately measured CKM matrix element.

(6) $|V_{ub}|$ – The decay $b \to u \ell \overline{\nu}$ and its charge conjugate can be observed from the semileptonic decay of B mesons produced on the $\Upsilon(4S)$ ($b\overline{b}$) resonance by measuring the lepton energy spectrum above the endpoint of the $b \to c \ell \overline{\nu}_\ell$ spectrum. There the $b \to u \ell \overline{\nu}_\ell$ decay rate can be obtained by subtracting the background from nonresonant e^+e^- reactions. This continuum background is determined from auxiliary measurements off the $\Upsilon(4S)$. The interpretation of the result in terms of $|V_{ub}/V_{cb}|$ depends fairly strongly on the theoretical model used to generate the lepton energy spectrum, especially for $b \to u$ transitions [21,22,27]. Combining the experimental and theoretical uncertainties, we quote

$$|V_{ub}/V_{cb}| = 0.08 \pm 0.02 \; . \qquad (11.14)$$

This result is supported by the first exclusive determinations of $|V_{ub}|$ from the decays $B \to \pi \ell \nu_\ell$ and $B \to \rho \ell \nu_\ell$ by the CLEO experiment [28] to obtain $|V_{ub}| = 3.3 \pm 0.4 \pm 0.7 \times 10^{-3}$, where the first error is experimental and the second reflects systematic uncertainty from different theoretical models of the exclusive decays. While this result is consistent with Eq. (11.14) and has a similar error bar, given the theoretical model dependence of both results we do not combine them, and retain the inclusive result for V_{ub}.

(7) V_{tb} – The discovery of the top quark by the CDF and DØ collaborations utilized in part the semileptonic decays of t to b. One can set a (still rather crude) limit on the fraction of decays of the form $t \to b \; \ell^+ \; \nu_\ell$, as opposed to semileptonic t decays that involve s or d quarks, of Ref. 29

$$\frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99 \pm 0.29 \; . \qquad (11.15)$$

For many of these CKM matrix elements, the primary source of error is no longer statistical, but rather theoretical. This arises from explicit model dependence in interpreting data or in the use of specific hadronic matrix elements to relate experimental measurements to weak transitions of quarks. This is even more the case in extracting CKM matrix elements from loop diagrams discussed below. Such errors are generally not Gaussian. We have taken a "1σ" range to correspond to a 68% likelihood that the true value lies within "$\pm 1\sigma$" of the central value.

The results for three generations of quarks, from Eqs. (11.7), (11.8), (11.9), (11.12), (11.13), (11.14), and (11.15) plus unitarity, are summarized in the matrix in Eq. (11.2). The ranges given there are different from those given in Eqs. (11.7)–(11.15) because of the inclusion of unitarity, but are consistent with the one-standard-deviation errors on the input matrix elements. Note in particular that the unitarity constraint has pushed $|V_{ud}|$ about one standard deviation higher than given in Eq. (11.7).

The data do not preclude there being more than three generations. Moreover, the entries deduced from unitarity might be altered when the CKM matrix is expanded to accommodate more generations. Conversely, the known entries restrict the possible values of additional elements if the matrix is expanded to account for additional generations. For example, unitarity and the known elements of the first row require that any additional element in the first row have a magnitude $|V_{ub'}| < 0.08$. When there are more than three generations, the allowed ranges (at 90% CL) of the matrix elements connecting the first three generations are

$$\begin{pmatrix} 0.9724 \text{ to } 0.9755 & 0.217 \text{ to } 0.223 & 0.0018 \text{ to } 0.0044 & \dots \\ 0.199 \text{ to } 0.232 & 0.847 \text{ to } 0.975 & 0.036 \text{ to } 0.042 & \dots \\ 0 \text{ to } 0.10 & 0 \text{ to } 0.36 & 0.05 \text{ to } 0.9994 & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix} , \qquad (11.16)$$

where we have used unitarity (for the expanded matrix) and the same measurements of the magnitudes of the CKM matrix elements.

Further information, particularly on CKM matrix elements involving the top quark, can be obtained from flavor-changing processes that occur at the one-loop level. We have not used this information in the discussion above since the derivation of values for V_{td} and V_{ts} in this manner from, for example, B mixing or $b \to s\gamma$, require an additional assumption that the top-quark loop, rather than new physics, gives the dominant contribution to the process in question. Conversely, the agreement of CKM matrix elements extracted from loop diagrams with the values based on direct measurements and three generations can be used to place restrictions on new physics.

The measured value [25] of $\Delta M_{B_d} = 0.472 \pm 0.018$ ps^{-1} from $B_d^0 - \overline{B}_d^0$ mixing can be turned in this way into information on $|V_{tb}^* V_{td}|$, assuming that the dominant contribution to the mass difference arises from the matrix element between a B_d and a $\overline{B}_d$ of an operator that corresponds to a box diagram with W bosons and top quarks as sides. Using the characteristic hadronic matrix element that then occurs, $\hat{B}_{B_d} f_{B_d}{}^2 = (1.4 \pm 0.1)(175 \pm 25 \text{ MeV})^2$ from lattice QCD calculations [30], which we regard as having become the most reliable source of such matrix elements, next-to-leading-order QCD corrections ($\eta_{\rm QCD} = 0.55$) [31], and the running top-quark mass, $\overline{m}_t(m_t) = 166 \pm 5$ GeV, as input,

$$|V_{tb}{}^* \cdot V_{td}| = 0.0084 \pm 0.0018 \ , \tag{11.17}$$

where the uncertainty comes primarily from that in the hadronic matrix elements, whose estimated errors are combined linearly.

In the ratio of B_s to B_d mass differences, many common factors (such as the QCD correction and dependence on the top-quark mass) cancel, and we have

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{M_{B_s}}{M_{B_d}} \frac{\widehat{B}_{B_s} f^2_{B_s}}{\widehat{B}_{B_d} f^2_{B_d}} \frac{|V^*_{tb} \cdot V_{ts}|^2}{|V^*_{tb} \cdot V_{td}|^2} \ . \tag{11.18}$$

With the experimentally measured masses [19], $\widehat{B}_{B_s}/\widehat{B}_{B_d} = 1.01 \pm 0.04$ and $f_{B_s}/f_{B_d} = 1.15 \pm 0.05$ from lattice QCD [30], and the improved experimental lower limit [25] at 95% CL of $\Delta M_{B_s} > 10.2$ ps^{-1},

$$|V_{td}|/|V_{ts}| < 0.27 \ . \tag{11.19}$$

Since with three generations, $|V_{ts}| \approx |V_{cb}|$, this result converts to $|V_{td}| < 0.011$, which is a significant constraint by itself (see Fig. 11.2).

The CLEO observation [32] of $b \to s\gamma$ can be translated [33] similarly into $|V_{ts}|/|V_{cb}| = 1.1 \pm 0.43$, where the large uncertainty is again dominantly theoretical. In $K^+ \to \pi^+ \nu\overline{\nu}$ there are significant contributions from loop-diagrams involving both charm and top quarks. Experiment is just begining to probe the level predicted in the Standard Model [34]. All these additional indirect constraints are consistent with the matrix elements obtained from the direct measurements plus unitarity, assuming three generations; with the recent results on B mixing and theoretical improvements in lattice calculations, adding the indirect constraints to the fit reduces the range allowed for $|V_{td}|$.

Direct and indirect information on the CKM matrix is neatly summarized in terms of the "unitarity triangle." The name arises since unitarity of the 3 × 3 CKM matrix applied to the first and third columns yields

$$V_{ud}\, V^*_{ub} + V_{cd}\, V^*_{cb} + V_{td} V^*_{tb} = 0 \ . \tag{11.20}$$

The unitarity triangle is just a geometrical presentation of this equation in the complex plane [35]. We can always choose to orient the triangle so that $V_{cd}\ V_{cb}{}^*$ lies along the horizontal; in the parametrization we have chosen, V_{cb} is real, and V_{cd} is real to a very good approximation in any case. Setting cosines of small angles to unity, Eq. (11.20) becomes

$$V_{ub}{}^* + V_{td} = s_{12}\ V_{cb}{}^* \ , \tag{11.21}$$

which is shown as the unitarity triangle in Fig. 11.1(a). Rescaling the triangle by a factor $[1/|s_{12}\ V_{cb}|]$ so that the base is of unit length, the coordinates of the vertices become

$$A(\mathrm{Re}(V_{ub})/|s_{12}\ V_{cb}| \ , \ -\mathrm{Im}(V_{ub})/|s_{12}\, V_{cb}|) \ , \ B(1,0) \ , \ C(0,0) \ . \tag{11.22}$$

In the Wolfenstein parametrization [4], the coordinates of the vertex A of the unitarity triangle are simply (ρ, η), as shown in Fig. 11.1(b).

CP-violating processes will involve the phase in the CKM matrix, assuming that the observed CP violation is solely related to a nonzero value of this phase. This allows additional constraints to be brought to bear. More specifically, a necessary and sufficient condition for CP violation with three generations can be formulated in a parametrization-independent manner in terms of the non-vanishing of the determinant of the commutator of the mass matrices for the charge $2e/3$ and charge $-e/3$ quarks [36]. CP violating amplitudes or differences of rates are all proportional to the CKM factor in this quantity. This is the product of factors $s_{12} s_{13} s_{23} c_{12} c^2_{13} c_{23} s_{\delta_{13}}$ in the parametrization adopted above, and is $s^2_1 s_2 s_3 c_1 c_2 c_3 s_\delta$ in that of Ref. 1. With the approximation of setting cosines to unity, this is just twice the area of the unitarity triangle.

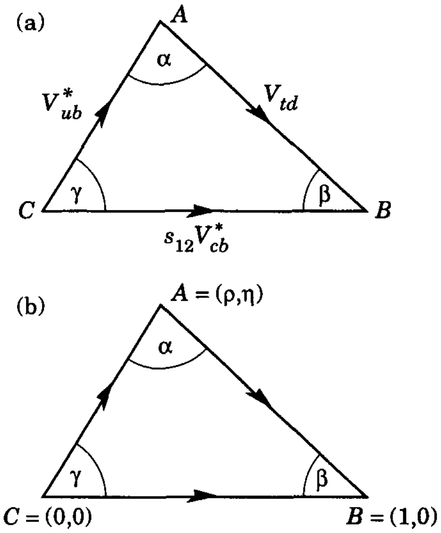

Figure 11.1: (a) Representation in the complex plane of the triangle formed by the CKM matrix elements $V_{ub}{}^*$, V_{td}, and $s_{12}\ V_{cb}{}^*$. (b) Rescaled triangle with vertices $A(\rho,\eta)$, $B(1,0)$, and $C(0,0)$.

While hadronic matrix elements whose values are imprecisely known generally enter the calculations, the constraints from CP violation in the neutral kaon system, taken together with the restrictions on the magnitudes of the CKM matrix elements shown above, are tight enough to restrict considerably the range of angles and the phase of the CKM matrix. For example, the constraint obtained from the CP-violating parameter ϵ in the neutral K system corresponds to the vertex A of the unitarity triangle lying on a hyperbola for fixed values of the hadronic matrix elements [37,38]. The constraints on the vertex of the unitarity triangle that follow from $|V_{ub}|$, B mixing, and ϵ are shown in Fig. 11.2. The improved limit in Eq. (11.19) that arises from the ratio of B_s to B_d mixing eliminates a significant region for the vertex A of the unitarity triangle, otherwise allowed by direct measurements of the CKM matrix elements. This limit is more robust theoretically since it depends on ratios (rather than absolute values) of hadronic matrix elements and is independent of the top mass or QCD corrections (which cancel in the ratio). Ultimately in the Standard Model, the CP-violating process $K_L \to \pi^0 \nu\overline{\nu}$ offers high precision in measuring the imaginary part of $V_{td} \cdot V_{ts}{}^*$ to yield Im V_{td}, the altitude of the unitarity triangle. However, the experimental upper limit is presently many orders of magnitude away from the requisite sensitivity.

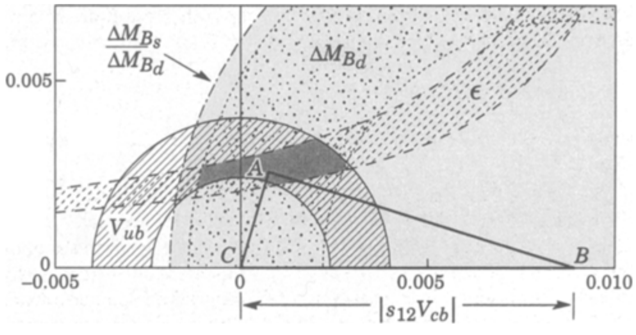

Figure 11.2: Constraints on the position of the vertex, A, of the unitarity triangle following from $|V_{ub}|$, B-mixing, and ϵ. A possible unitarity triangle is shown with A in the preferred region.

For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry in a given decay and $\sin 2\phi$, where $\phi = \alpha$, β, γ is an appropriate angle of the unitarity triangle [35]. The combination of all the direct and indirect information can be used to find the implications for future measurements of CP violation in the B system. (See Sec. 12 on CP Violation and the review on "CP Violation in B Decay – Standard Model Predictions" in the B Listings.)

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12. *CP* VIOLATION

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The symmetries C (particle-antiparticle interchange) and P (space inversion) hold for strong and electromagnetic interactions. After the discovery of large C and P violation in the weak interactions, it appeared that the product CP was a good symmetry. In 1964 CP violation was observed in K^0 decays at a level given by the parameter $\epsilon \approx 2.3 \times 10^{-3}$. Larger CP-violation effects are anticipated in B^0 decays.

12.1. *CP* violation in Kaon decay

CP violation has been observed in the semi-leptonic decays $K^0_L \to \pi^{\mp}\ell^{\pm}\nu$ and in the nonleptonic decay $K^0_L \to 2\pi$. The experimental numbers that have been measured are

$$\delta = \frac{\Gamma(K^0_L \to \pi^-\ell^+\nu) - \Gamma(K^0_L \to \pi^+\ell^-\nu)}{\Gamma(K^0_L \to \pi^-\ell^+\nu) + \Gamma(K^0_L \to \pi^+\ell^-\nu)} \qquad (12.1a)$$

$$\begin{aligned} \eta_{+-} &= A(K^0_L \to \pi^+\pi^-)/A(K^0_S \to \pi^+\pi^-) \\ &= |\eta_{+-}|\, e^{i\phi_{+-}} \qquad (12.1b) \\ \eta_{00} &= A(K^0_L \to \pi^0\pi^0)/A(K^0_S \to \pi^0\pi^0) \\ &= |\eta_{00}|\, e^{i\phi_{00}} \ . \qquad (12.1c) \end{aligned}$$

Thus there are five real numbers, three magnitudes, and two phases. The present data gives $|\eta_{+-}| \approx |\eta_{00}| = 2.28 \times 10^{-3}$, $\phi_{+-} \approx \phi_{00} = 44^\circ$, and $\delta = 3.3 \times 10^{-3}$.

CP violation can occur either in the K^0-$\overline{K}^0$ mixing or in the decay amplitudes. Assuming CPT invariance, the mass eigenstates of the K^0-$\overline{K}^0$ system can be written

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle \ , \qquad |K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle \ . \qquad (12.2)$$

If CP invariance held, we would have $q = p$ so that K_S would be CP even and K_L CP odd. (We define $|\overline{K}^0\rangle$ as $CP\ |K^0\rangle$). CP violation in K^0-$\overline{K}^0$ mixing is then given by the parameter $\widetilde{\epsilon}$ where

$$\frac{p}{q} = \frac{(1+\widetilde{\epsilon})}{(1-\widetilde{\epsilon})} \ . \qquad (12.3)$$

CP violation can also occur in the decay amplitudes

$$A(K^0 \to \pi\pi(I)) = A_I e^{i\delta_I} \ , \qquad A(\overline{K}^0 \to \pi\pi(I)) = A_I^* e^{i\delta_I} \ , \quad (12.4)$$

where I is the isospin of $\pi\pi$, δ_I is the final-state phase shift, and A_I would be real if CP invariance held. The CP-violating observables are usually expressed in terms of ϵ and ϵ' defined by

$$\eta_{+-} = \epsilon + \epsilon' \ , \qquad \eta_{00} = \epsilon - 2\epsilon' \ , \qquad (12.5a)$$

One can then show [1]

$$\epsilon = \widetilde{\epsilon} + i\ \left(\text{Im}\, A_0/\text{Re}\, A_0\right) \ , \qquad (12.5b)$$

$$\sqrt{2}\epsilon' = ie^{i(\delta_2-\delta_0)}(\text{Re}\, A_2/\text{Re}\, A_0)\ \left(\text{Im}\, A_2/\text{Re}\, A_2 - \text{Im}\, A_0/\text{Re}\, A_0\right) \ , \qquad (12.5c)$$

$$\delta = 2\text{Re}\, \epsilon/(1+|\epsilon|^2) \approx 2\text{Re}\, \epsilon \ . \qquad (12.5d)$$

In Eq. (12.5c) small corrections of order $\epsilon' \times \text{Re}\ (A_2/A_0)$ are neglected and Eq. (12.5d) assumes the $\Delta S = \Delta Q$ rule.

The quantities Im A_0, Im A_2, and Im ϵ depend on the choice of phase convention since one can change the phases of K^0 and $\overline{K}^0$ by a transformation of the strange quark state $|s\rangle \to |s\rangle\ e^{i\alpha}$; of course, observables are unchanged. It is possible by a choice of phase convention to set Im A_0 or Im A_2 or Im $\widetilde{\epsilon}$ to zero, but none of these is zero may be the usual phase conventions in the Standard Model. The choice Im $A_0 = 0$ is called the Wu-Yang phase convention [2] in which case $\epsilon = \widetilde{\epsilon}$. The value of ϵ' is independent of phase convention and a nonzero value would demonstrate CP violation in the decay amplitudes, referred to as direct CP violation. The possibility that direct CP violation is essentially zero and that CP violation occurs only in the mixing matrix is referred to as the superweak theory [3].

By applying CPT invariance and unitarity the phase of ϵ is given approximately by

$$\phi(\epsilon) \approx \tan^{-1}\frac{2(m_{K_L} - m_{K_S})}{\Gamma_{K_S} - \Gamma_{K_L}} = 43.49 \pm 0.08^\circ \qquad (12.6a)$$

while Eq. (12.5c) gives

$$\phi(\epsilon') = \delta_2 - \delta_0 + \frac{\pi}{2} \approx 48 \pm 4^\circ \ , \qquad (12.6b)$$

where the numerical value is based on an analysis of π-π scattering [4]. The approximation in Eq. (12.6a) depends on the assumption that direct CP violation is very small in all K^0 decays. This is expected to be good to a few tenths of a degree as indicated by the small value of ϵ' and of η_{+-0}, the CP violation parameter in the decay $K_S \to \pi^+\pi^-\pi^0$ [5], although limits on η_{000} are still poor. The relation in Eq. (12.6a) is exact in the superweak theory so this is sometimes called the superweak phase. The most important point for the analysis is that $\cos[\phi(\epsilon') - \phi(\epsilon)] \simeq 1$. The consequence is that only two real quantities need be measured, the magnitude of ϵ and the value of (ϵ'/ϵ) including its sign. The measured quantity $|\eta_{00}/\eta_{+-}|^2$, which is very close to unity, is given to a good approximation by

$$|\eta_{00}/\eta_{+-}|^2 \approx 1 - 6\text{Re}\ (\epsilon'/\epsilon) \approx 1 - 6\epsilon'/\epsilon \ . \qquad (12.7)$$

The values of ϕ_{+-} and $\phi_{00} - \phi_{+-}$ are used to set limits on CPT violation. [See Tests of Conservation Laws.]

In the Standard Model, CP violation arises as a result of a single phase entering the CKM matrix (Sec. 11). As a result in what is now the standard phase convention, two elements have large phases, $V_{ub} \sim e^{-i\gamma}$, $V_{td} \sim e^{-i\beta}$. Because these elements have small magnitudes and involve the third generation, CP violation in the K^0 system is small. In general a nonzero value for ϵ'/ϵ is expected but uncertainties in evaluating hadronic matrix elements make the prediction uncertain. Most theoretical calculations [6] give a value between zero and 10^{-3}, but somewhat larger values or small negative values may be possible. On the other hand, large effects are expected in the B^0 system, which is a major motivation for B factories.

12.2. *CP* violation in *B* decay

CP violation in the B^0 system can be observed by comparing B^0 and $\overline{B}^0$ decays [7]. For a final CP eigenstate a, the decay rate has a time dependence given by

$$\Gamma_a \sim e^{-\Gamma t}\Big([1 + |\lambda_a|^2] \pm [1 - |\lambda_a|^2]\ \cos(\Delta M t) \mp \text{Im}\ \lambda_a\ \ \sin(\Delta M t)\Big) \qquad (12.8)$$

where the top sign is for B^0 and the bottom for $\overline{B}^0$ and

$$\lambda_a = (q_B/p_B)\ \overline{A}_a/A_a \ . \qquad (12.9)$$

The quantities p_B and q_B come from the analogue for B^0 of Eq. (12.2), and $A_a(\overline{A}_a)$ is the decay amplitude to state a for $B^0(\overline{B}^0)$. However, for B^0 the eigenstates are expected to have a negligible lifetime difference and are only distinguished by the mass difference ΔM; also as a consequence $|q_B/p_B| \approx 1$ so that $\widetilde{\epsilon}_B$ is purely imaginary.

If only one quark weak transition contributes to the decay, $|\overline{A}_a/A_a| = 1$ so that $|\lambda_a| = 1$ and the $\cos(\Delta M t)$ term vanishes. In this case, the difference between B^0 and $\overline{B}^0$ decays is given by the $\sin(\Delta M t)$ term with the asymmetry coefficient

$$a_a = \frac{\Gamma_a(t) - \overline{\Gamma}_a(t)}{(\Gamma_a(t) + \overline{\Gamma}_a(t))\sin(\Delta M t)} = \eta_a \sin\Big(2(\phi_M + \phi_D)\Big) \ , \qquad (12.10)$$

where $2\phi_M$ is the phase of the B^0–$\overline{B}^0$ mixing, ϕ_D is the weak phase of the decay transition, and η_a is the CP eigenvalue of a.

For $B^0(\overline{B}^0) \rightarrow \psi K_S$ from the transition $b \rightarrow c\bar{c}s$, one finds in the Standard Model that the asymmetry is given directly in terms of a CKM phase with no hadronic uncertainty:

$$a_{\psi K_S} = -\sin 2\beta \ . \tag{12.11}$$

From the constraints on the CKM matrix (Sec. 11) $\sin 2\beta$ is predicted to be between 0.3 and 0.9. A significantly different value could be a sign of new physics.

A second decay of interest is B^0 $(\overline{B}^0) \rightarrow \pi^+\pi^-$ from the transition $b \rightarrow u\bar{u}d$ with

$$a_{\pi\pi} = \sin 2(\beta + \gamma) \ . \tag{12.12}$$

While either of these asymmetries could be ascribed to B^0–$\overline{B}^0$ mixing (q_B/p_B or $\overline{\epsilon}_B$), the difference between the two asymmetries is evidence for direct CP violation. From Eq. (12.9) it is seen that this corresponds to a phase difference between $A_{\psi K_S}$ and $A_{\pi^+\pi^-}$. Thus this is analogous to ϵ'. In the standard phase convention, 2β in Eqs. (12.11) and (12.12) arises from B^0–$\overline{B}^0$ mixing whereas the γ in Eq. (12.12) comes from V_{ub} in the transition $b \rightarrow u\bar{u}d$. The result in Eq. (12.12) may have a sizeable correction due to what is called a penguin diagram. This is a one-loop graph producing $b \rightarrow d +$ gluon with a W and a quark, predominantly the t quark, in the loop. This leads to an amplitude proportional to $V_{tb}^* V_{td}$, which has a weak phase different from that of the original tree amplitude proportional to $V_{ub}V_{ud}^*$. There are several methods to approximately determine this correction using additional measurements [8].

CP violation in the decay amplitude is also revealed by the $\cos(\Delta M t)$ term in Eq. (12.8) or by a difference in rates of B^+ and B^- to charge-conjugate states. These effects, however, require two contributing amplitudes to the decay (such as a tree amplitude plus a penguin) and also require final-state interaction phases. Predicted effects are very uncertain and are generally small [9].

In the case of the B_s system, the mass difference ΔM is much larger than for B^0 and has not yet been measured. As a result, it will be difficult to isolate the $\sin(\Delta M t)$ term to measure asymmetries. Furthermore, in the Standard Model with the standard phase convention, ϕ_M is very small so that decays due to $b \rightarrow c\bar{c}s$, yielding $B_s \rightarrow \psi\eta'$, would have zero asymmetry. Decays due to $b \rightarrow u\bar{u}d$, yielding $B_s \rightarrow \rho^0 K_S$, would have an asymmetry $\sin 2\gamma$ in the tree approximation. The width difference $\Delta\Gamma$ is also expected to be much larger for B_s so that $\Delta\Gamma/\Gamma$ might be as large as 0.15. In this case, there might be a possibility of detecting CP violation as in the case of K^0 by observing the B_s states with different lifetimes decaying into the same CP eigenstate [10].

For further details, see the notes on CP violation in the K_L^0, K_S^0, and B^0 Particle Listings of this *Review*.

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13. QUARK MODEL

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13.1. Quantum numbers of the quarks

Each quark has spin 1/2 and baryon number 1/3. Table 13.1 gives the additive quantum numbers (other than baryon number) of the three generations of quarks. Our convention is that the *flavor* of a quark (I_z, S, C, B, or T) has the same sign as its *charge*. With this convention, any flavor carried by a *charged* meson has the same sign as its charge; *e.g.*, the strangeness of the K^+ is +1, the bottomness of the B^+ is +1, and the charm *and* strangeness of the D_s^- are each −1.

By convention, each quark is assigned positive parity. Then each antiquark has negative parity.

Table 13.1: Additive quantum numbers of the quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

13.2. Mesons: $q\overline{q}$ states

Nearly all known mesons are bound states of a quark q and an antiquark $\overline{q}'$ (the flavors of q and q' may be different). If the orbital angular momentum of the $q\overline{q}'$ state is L, then the parity P is $(-1)^{L+1}$. A state $q\overline{q}$ of a quark and its own antiquark is also an eigenstate of charge conjugation, with $C = (-1)^{L+S}$, where the spin S is 0 or 1. The $L = 0$ states are the pseudoscalars, $J^P = 0^-$, and the vectors, $J^P = 1^-$. Assignments for many of the known mesons are given in Table 13.2. States in the "normal" spin-parity series, $P = (-1)^J$, must, according to the above, have $S = 1$ and hence $CP = +1$. Thus mesons with normal spin-parity and $CP = -1$ are forbidden in the $q\overline{q}'$ model. The $J^{PC} = 0^{--}$ state is forbidden as well. Mesons with such J^{PC} may exist, but would lie outside the $q\overline{q}'$ model.

The nine possible $q\overline{q}'$ combinations containing u, d, and s quarks group themselves into an octet and a singlet:

$$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1} \tag{13.1}$$

States with the same IJ^P and additive quantum numbers can mix. (If they are eigenstates of charge conjugation, they must also have the same value of C.) Thus the $I = 0$ member of the ground-state pseudoscalar octet mixes with the corresponding pseudoscalar singlet to produce the η and η'. These appear as members of a nonet, which is shown as the middle plane in Fig. 13.1(a). Similarly, the ground-state vector nonet appears as the middle plane in Fig. 13.1(b).

A fourth quark such as charm can be included in this scheme by extending the symmetry to SU(4), as shown in Fig. 13.1. Bottom extends the symmetry to SU(5); to draw the multiplets would require four dimensions.

For the pseudoscalar mesons, the Gell-Mann-Okubo formula is

$$m_\eta^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)\ , \tag{13.2}$$

assuming no octet-singlet mixing. However, the octet η_8 and singlet η_1 mix because of SU(3) breaking. In general, the mixing angle is mass dependent and becomes complex for resonances of finite width. Neglecting this, the physical states η and η' are given in terms of a mixing angle θ_P by

$$\eta = \eta_8 \cos\theta_P - \eta_1 \sin\theta_P \tag{13.3a}$$

$$\eta' = \eta_8 \sin\theta_P + \eta_1 \cos\theta_P\ . \tag{13.3b}$$

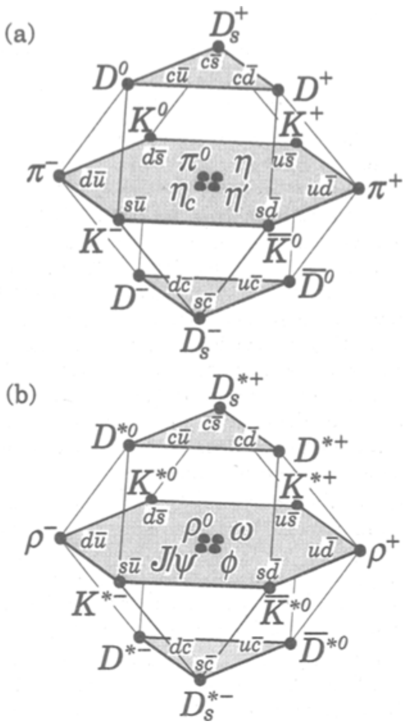

Figure 13.1: SU(4) 16-plets for the (a) pseudoscalar and (b) vector mesons made of u, d, s, and c quarks. The nonets of light mesons occupy the central planes, to which the $c\overline{c}$ states have been added. The neutral mesons at the centers of these planes are mixtures of $u\overline{u}$, $d\overline{d}$, $s\overline{s}$, and $c\overline{c}$ states.

These combinations diagonalize the mass-squared matrix

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{18}^2 \\ M_{18}^2 & M_{88}^2 \end{pmatrix}\ , \tag{13.4}$$

where $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)$. It follows that

$$\tan^2\theta_P = \frac{M_{88}^2 - m_\eta^2}{m_{\eta'}^2 - M_{88}^2}\ . \tag{13.5}$$

The sign of θ_P is meaningful in the quark model. If

$$\eta_1 = (u\overline{u} + d\overline{d} + s\overline{s})/\sqrt{3} \tag{13.6a}$$

$$\eta_8 = (u\overline{u} + d\overline{d} - 2s\overline{s})/\sqrt{6}\ , \tag{13.6b}$$

then the matrix element M_{18}^2, which is due mostly to the strange quark mass, is negative. From the relation

$$\tan\theta_P = \frac{M_{88}^2 - m_\eta^2}{M_{18}^2}\ , \tag{13.7}$$

we find that $\theta_P < 0$. However, caution is suggested in the use of the η-η' mixing-angle formulas, as they are extremely sensitive to SU(3)

Table 13.2: Suggested $q\bar{q}$ quark-model assignments for most of the known mesons. Some assignments, especially for the 0^{++} multiplet and for some of the higher multiplets, are controversial. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the $f_0(1500)$, $f_1(1510)$, $f_J(1710)$, $f_2(2300)$, $f_2(2340)$, and one of the two peaks in the $\eta(1440)$ entry are not in this table. Within the $q\bar{q}$ model, it is especially hard to find a place for the first three of these f mesons and for one of the $\eta(1440)$ peaks. See the "Note on Non-$q\bar{q}$ Mesons" at the end of the Meson Listings.

$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$	$b\bar{b}$ $I=0$	$\bar{s}u$, $\bar{s}d$ $I=1/2$	$c\bar{u}$, $c\bar{d}$ $I=1/2$	$c\bar{s}$ $I=0$	$\bar{b}u$, $\bar{b}d$ $I=1/2$	$\bar{b}s$ $I=0$	$\bar{b}c$ $I=0$
$1\ ^1S_0$	0^{-+}	$\boldsymbol{\pi}$	$\boldsymbol{\eta}$, $\boldsymbol{\eta'}$	$\boldsymbol{\eta_c}$		$\boldsymbol{K}$	$\boldsymbol{D}$	$\boldsymbol{D_s}$	$\boldsymbol{B}$	$\boldsymbol{B_s}$	B_c
$1\ ^3S_1$	1^{--}	$\boldsymbol{\rho}$	$\boldsymbol{\omega}$, $\boldsymbol{\phi}$	$\boldsymbol{J/\psi(1S)}$	$\boldsymbol{\Upsilon(1S)}$	$\boldsymbol{K^*(892)}$	$\boldsymbol{D^*(2010)}$	$\boldsymbol{D_s^*}$	$\boldsymbol{B^*}$	B_s^*	
$1\ ^1P_1$	1^{+-}	$\boldsymbol{b_1(1235)}$	$\boldsymbol{h_1(1170)}$, $h_1(1380)$	$h_c(1P)$		$\boldsymbol{K_{1B}}$[†]	$\boldsymbol{D_1(2420)}$	$\boldsymbol{D_{s1}(2536)}$			
$1\ ^3P_0$	0^{++}	$\boldsymbol{a_0(1450)}$*	$\boldsymbol{f_0(1370)}$*	$\boldsymbol{\chi_{c0}(1P)}$	$\boldsymbol{\chi_{b0}(1P)}$	$\boldsymbol{K_0^*(1430)}$					
$1\ ^3P_1$	1^{++}	$\boldsymbol{a_1(1260)}$	$\boldsymbol{f_1(1285)}$, $\boldsymbol{f_1(1420)}$	$\boldsymbol{\chi_{c1}(1P)}$	$\boldsymbol{\chi_{b1}(1P)}$	$\boldsymbol{K_{1A}}$[†]					
$1\ ^3P_2$	2^{++}	$\boldsymbol{a_2(1320)}$	$\boldsymbol{f_2(1270)}$, $\boldsymbol{f_2'(1525)}$	$\boldsymbol{\chi_{c2}(1P)}$	$\boldsymbol{\chi_{b2}(1P)}$	$\boldsymbol{K_2^*(1430)}$	$\boldsymbol{D_2^*(2460)}$				
$1\ ^1D_2$	2^{-+}	$\boldsymbol{\pi_2(1670)}$	$\eta_2(1645)$, $\eta_2(1870)$			$\boldsymbol{K_2(1770)}$					
$1\ ^3D_1$	1^{--}	$\boldsymbol{\rho(1700)}$	$\boldsymbol{\omega(1600)}$	$\boldsymbol{\psi(3770)}$		$\boldsymbol{K^*(1680)}$[‡]					
$1\ ^3D_2$	2^{--}					$\boldsymbol{K_2(1820)}$					
$1\ ^3D_3$	3^{--}	$\boldsymbol{\rho_3(1690)}$	$\boldsymbol{\omega_3(1670)}$, $\boldsymbol{\phi_3(1850)}$			$\boldsymbol{K_3^*(1780)}$					
$1\ ^3F_4$	4^{++}	$\boldsymbol{a_4(2040)}$	$\boldsymbol{f_4(2050)}$, $f_4(2220)$			$\boldsymbol{K_4^*(2045)}$					
$2\ ^1S_0$	0^{-+}	$\boldsymbol{\pi(1300)}$	$\boldsymbol{\eta(1295)}$, $\boldsymbol{\eta(1440)}$	$\boldsymbol{\eta_c(2S)}$		$K(1460)$					
$2\ ^3S_1$	1^{--}	$\boldsymbol{\rho(1450)}$	$\boldsymbol{\omega(1420)}$, $\boldsymbol{\phi(1680)}$	$\boldsymbol{\psi(2S)}$	$\boldsymbol{\Upsilon(2S)}$	$\boldsymbol{K^*(1410)}$[‡]					
$2\ ^3P_2$	2^{++}		$f_2(1810)$, $\boldsymbol{f_2(2010)}$		$\boldsymbol{\chi_{b2}(2P)}$	$K_2^*(1980)$					
$3\ ^1S_0$	0^{-+}	$\boldsymbol{\pi(1800)}$	$\eta(1760)$			$K(1830)$					

* See our scalar minireview in the Particle Listings. The candidates for the $I=1$ states are $a_0(980)$ and $a_0(1450)$, while for $I=0$ they are: $f_0(400\text{–}1200)$, $f_0(980)$, and $f_0(1370)$. The light scalars are problematic, since there may be two poles for one $q\bar{q}$ state and $a_0(980)$, $f_0(980)$ may be $K\overline{K}$ bound states.

[†] The K_{1A} and K_{1B} are nearly equal (45°) mixes of the $K_1(1270)$ and $K_1(1400)$.

[‡] The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\ ^3S_1$ state.

If we allow $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)\ (1+\Delta)$, the mixing angle is determined by

$$\tan^2\theta_P = 0.0319(1+17\Delta) \tag{13.8}$$

$$\theta_P = -10.1°(1+8.5\Delta) \tag{13.9}$$

to first order in Δ. A small breaking of the Gell-Mann-Okubo relation can produce a major modification of θ_P.

For the vector mesons, $\pi \to \rho$, $K \to K^*$, $\eta \to \phi$, and $\eta' \to \omega$, so that

$$\phi = \omega_8 \cos\theta_V - \omega_1 \sin\theta_V \tag{13.10}$$

$$\omega = \omega_8 \sin\theta_V + \omega_1 \cos\theta_V\ . \tag{13.11}$$

For "ideal" mixing, $\phi = s\bar{s}$, so $\tan\theta_V = 1/\sqrt{2}$ and $\theta_V = 35.3°$. Experimentally, θ_V is near 35°, the sign being determined by a formula like that for $\tan\theta_P$. Following this procedure we find the mixing angles given in Table 13.3.

Table 13.3: Singlet-octet mixing angles for several nonets, neglecting possible mass dependence and imaginary parts. The sign conventions are given in the text. The values of $\theta_{\rm quad}$ are obtained from the equations in the text, while those for $\theta_{\rm lin}$ are obtained by replacing m^2 by m throughout. Of the two isosinglets in a nonet, the mostly octet one is listed first.

J^{PC}	Nonet members	$\theta_{\rm quad}$	$\theta_{\rm lin}$
0^{-+}	π, K, η, η'	−10°	−23°
1^{--}	ρ, $K^*(892)$, ϕ, ω	39°	36°
2^{++}	$a_2(1320)$, $K_2^*(1430)$, $f_2'(1525)$, $f_2(1270)$	28°	26°
3^{--}	$\rho_3(1690)$, $K_3^*(1780)$, $\phi_3(1850)$, $\omega_3(1670)$	29°	28°

In the quark model, the coupling of neutral mesons to two photons is proportional to $\sum_i Q_i^2$, where Q_i is the charge of the i-th quark. This provides an alternative characterization of mixing. For example, defining

$$\mathrm{Amp}\,[P \to \gamma(k_1)\,\gamma(k_2)] = M\epsilon^{\mu\nu\alpha\beta}\,\epsilon^*_{1\mu}\,k_{1\nu}\,\epsilon^*_{2\alpha}\,k_{2\beta}\ , \qquad (13.12)$$

where $\epsilon_{i\lambda}$ is the λ component of the polarization vector of the i^{th} photon, one finds

$$\begin{aligned}\frac{M(\eta \to \gamma\gamma)}{M(\pi^0 \to \gamma\gamma)} &= \frac{1}{\sqrt{3}}(\cos\theta_P - 2\sqrt{2}\sin\theta_P)\\ &= \frac{1.73 \pm 0.18}{\sqrt{3}} \qquad (13.13a)\\ \frac{M(\eta' \to \gamma\gamma)}{M(\pi^0 \to \gamma\gamma)} &= 2\sqrt{2/3}\left(\cos\theta_P + \frac{\sin\theta_P}{2\sqrt{2}}\right)\\ &= 2\sqrt{2/3}\,(0.78 \pm 0.04)\ , \qquad (13.13b)\end{aligned}$$

where the numbers with errors are experimental. These data favor $\theta_P \approx -20°$, which is compatible with the quadratic mass mixing formula with about 12% SU(3) breaking in M^2_{88}.

13.3. Baryons: *qqq* states

All the established baryons are apparently 3-quark (qqq) states, and each such state is an SU(3) color singlet, a completely antisymmetric state of the three possible colors. Since the quarks are fermions, the state function for any baryon must be antisymmetric under interchange of any two equal-mass quarks (up and down quarks in the limit of isospin symmetry). Thus the state function may be written as

$$|\,qqq\,\rangle_A = |\,\mathrm{color}\,\rangle_A \times |\,\mathrm{space,\ spin,\ flavor}\,\rangle_S\ , \qquad (13.14)$$

where the subscripts S and A indicate symmetry or antisymmetry under interchange of any two of the equal-mass quarks. Note the contrast with the state function for the three nucleons in ^{3}H or ^{3}He:

$$|\,NNN\,\rangle_A = |\,\mathrm{space,\ spin,\ isospin}\,\rangle_A\ . \qquad (13.15)$$

This difference has major implications for internal structure, magnetic moments, *etc.* (For a nice discussion, see Ref. 1.)

The "ordinary" baryons are made up of u, d, and s quarks. The three flavors imply an approximate flavor SU(3), which requires that baryons made of these quarks belong to the multiplets on the right side of

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A \qquad (13.16)$$

(see Sec. 34, on "SU(n) Multiplets and Young Diagrams"). Here the subscripts indicate symmetric, mixed-symmetry, or antisymmetric states under interchange of any two quarks. The **1** is a uds state (Λ_1) and the octet contains a similar state (Λ_8). If these have the same spin and parity they can mix. An example is the mainly octet D_{03} $\Lambda(1690)$ and mainly singlet D_{03} $\Lambda(1520)$. In the ground state multiplet, the SU(3) flavor singlet Λ is forbidden by Fermi statistics. The mixing formalism is the same as for η-η' or ϕ-ω (see above), except that for baryons the mass M instead of M^2 is used. Section 33, on "SU(3) Isoscalar Factors and Representation Matrices", shows how relative decay rates in, say, $\mathbf{10} \to \mathbf{8} \otimes \mathbf{8}$ decays may be calculated. A summary of results of fits to the observed baryon masses and decay rates for the best-known SU(3) multiplets is given in Appendix II of our 1982 edition [2].

The addition of the c quark to the light quarks extends the flavor symmetry to SU(4). Figures 13.2(a) and 13.2(b) show the (badly broken) SU(4) baryon multiplets that have as their "ground floors" the SU(3) octet that contains the nucleons and the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark. These belong to the first floor of the multiplet shown in Fig. 13.2(a); for details, see the "Note on Charmed Baryons" in the Baryon Particle Listings. The addition of a b quark extends the flavor symmetry to SU(5); it would require four dimensions to draw the multiplets.

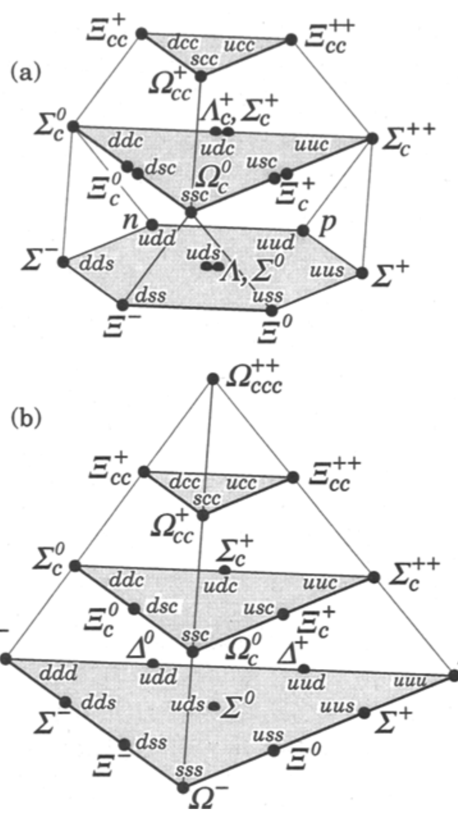

Figure 13.2: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

For the "ordinary" baryons, flavor and spin may be combined in an approximate flavor-spin SU(6) in which the six basic states are $d\uparrow$, $d\downarrow$, $\cdots$, $s\downarrow$ ($\uparrow$, $\downarrow$ = spin up, down). Then the baryons belong to the multiplets on the right side of

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A\ . \qquad (13.17)$$

These SU(6) multiplets decompose into flavor SU(3) multiplets as follows:

$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8} \qquad (13.18a)$$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1} \qquad (13.18b)$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1}\ , \qquad (13.18c)$$

where the superscript $(2S+1)$ gives the net spin S of the quarks for each particle in the SU(3) multiplet. The $J^P = 1/2^+$ octet containing the nucleon and the $J^P = 3/2^+$ decuplet containing the $\Delta(1232)$ together make up the "ground-state" 56-plet in which the orbital angular momenta between the quark pairs are zero (so that the spatial part of the state function is trivially symmetric). The **70** and **20** require some excitation of the spatial part of the state function in order to make the overall state function symmetric. States with nonzero orbital angular momenta are classified in SU(6)⊗O(3) supermultiplets. Physical baryons with the same quantum numbers do not belong to a single supermultiplet, since SU(6) is broken by spin-dependent interactions, differences in quark masses, *etc.* Nevertheless, the SU(6)⊗O(3) basis provides a suitable framework for describing baryon state functions.

It is useful to classify the baryons into bands that have the same number N of quanta of excitation. Each band consists of a number of supermultiplets, specified by (D, L_N^P), where D is the dimensionality of the SU(6) representation, L is the total quark orbital angular momentum, and P is the total parity. Supermultiplets contained in bands up to $N = 12$ are given in Ref. 3. The $N = 0$ band, which contains the nucleon and $\Delta(1232)$, consists only of the $(56,0_0^+)$ supermultiplet. The $N = 1$ band consists only of the $(70,1_1^-)$ multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The $N = 2$ band contains five supermultiplets: $(56,0_2^+)$, $(70,0_2^+)$, $(56,2_2^+)$, $(70,2_2^+)$, and $(20,1_2^+)$. Baryons belonging to the $(20,1_2^+)$ supermultiplet are not ever likely to be observed, since a coupling from the ground-state baryons requires a two-quark excitation. Selection rules are similarly responsible for the fact that many other baryon resonances have not been observed [4].

In Table 13.4, quark-model assignments are given for many of the established baryons whose SU(6)⊗O(3) compositions are relatively unmixed. We note that the unestablished resonances $\Sigma(1480)$, $\Sigma(1560)$, $\Sigma(1580)$, $\Sigma(1770)$, and $\Xi(1620)$ in our Baryon Particle Listings are too low in mass to be accommodated in most quark models [4,5].

Table 13.4: Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for the $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses.

J^P	(D,L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

The quark model for baryons is extensively reviewed in Ref. 6 and 7.

13.4. Dynamics

Many specific quark models exist, but most contain the same basic set of dynamical ingredients. These include:

i) A confining interaction, which is generally spin-independent.

ii) A spin-dependent interaction, modeled after the effects of gluon exchange in QCD. For example, in the S-wave states, there is a spin-spin hyperfine interaction of the form

$$H_{HF} = -\alpha_S M \sum_{i>j} (\vec{\sigma}\lambda_a)_i (\vec{\sigma}\lambda_a)_j \ , \tag{13.19}$$

where M is a constant with units of energy, λ_a $(a = 1, \cdots, 8,)$ is the set of SU(3) unitary spin matrices, defined in Sec. 33, on "SU(3) Isoscalar Factors and Representation Matrices," and the sum runs over constituent quarks or antiquarks. Spin-orbit interactions, although allowed, seem to be small.

iii) A strange quark mass somewhat larger than the up and down quark masses, in order to split the SU(3) multiplets.

iv) In the case of isoscalar mesons, an interaction for mixing $q\bar{q}$ configurations of different flavors (*e.g.*, $u\bar{u} \leftrightarrow d\bar{d} \leftrightarrow s\bar{s}$), in a manner which is generally chosen to be flavor independent.

These four ingredients provide the basic mechanisms that determine the hadron spectrum.

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14. EXPERIMENTAL TESTS OF GRAVITATIONAL THEORY

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Einstein's General Relativity, the current "standard" theory of gravitation, describes gravity as a universal deformation of the Minkowski metric:

$$g_{\mu\nu}(x^\lambda) = \eta_{\mu\nu} + h_{\mu\nu}(x^\lambda)\ , \text{ where } \eta_{\mu\nu} = \mathrm{diag}(-1,+1,+1,+1)\ . \quad (14.1)$$

Alternatively, it can be defined as the unique, consistent, local theory of a massless spin-2 field $h_{\mu\nu}$, whose source must then be the total, conserved energy-momentum tensor [1]. General Relativity is classically defined by two postulates. One postulate states that the Lagrangian density describing the propagation and self-interaction of the gravitational field is

$$\mathcal{L}_{\mathrm{Ein}}[g_{\mu\nu}] = \frac{c^4}{16\pi G_N}\sqrt{g}g^{\mu\nu}R_{\mu\nu}(g)\ , \quad (14.2)$$

$$R_{\mu\nu}(g) = \partial_\alpha\Gamma^\alpha_{\mu\nu} - \partial_\nu\Gamma^\alpha_{\mu\alpha} + \Gamma^\beta_{\alpha\beta}\Gamma^\alpha_{\mu\nu} - \Gamma^\beta_{\nu\alpha}\Gamma^\alpha_{\mu\beta}\ , \quad (14.3)$$

$$\Gamma^\lambda_{\mu\nu} = \tfrac{1}{2}g^{\lambda\sigma}(\partial_\mu g_{\nu\sigma} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu})\ , \quad (14.4)$$

where G_N is Newton's constant, $g = -\det(g_{\mu\nu})$, and $g^{\mu\nu}$ is the matrix inverse of $g_{\mu\nu}$. A second postulate states that $g_{\mu\nu}$ couples universally, and minimally, to all the fields of the Standard Model by replacing everywhere the Minkowski metric $\eta_{\mu\nu}$. Schematically (suppressing matrix indices and labels for the various gauge fields and fermions and for the Higgs doublet),

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}}[\psi, A_\mu, H, g_{\mu\nu}] = &-\tfrac{1}{4}\sum\sqrt{g}g^{\mu\alpha}g^{\nu\beta}F^a_{\mu\nu}F^a_{\alpha\beta}\\ &-\sum\sqrt{g}\,\overline{\psi}\,\gamma^\mu D_\mu\psi\\ &-\tfrac{1}{2}\sqrt{g}g^{\mu\nu}\overline{D_\mu H}D_\nu H - \sqrt{g}\,V(H)\\ &-\sum\lambda\sqrt{g}\,\overline{\psi}\,H\psi\ , \end{aligned} \quad (14.5)$$

where $\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$, and where the covariant derivative D_μ contains, besides the usual gauge field terms, a (spin dependent) gravitational contribution $\Gamma_\mu(x)$ [2]. From the total action $S_{\mathrm{tot}}[g_{\mu\nu}, \psi, A_\mu, H] = c^{-1}\int d^4x(\mathcal{L}_{\mathrm{Ein}} + \mathcal{L}_{\mathrm{SM}})$ follow Einstein's field equations,

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G_N}{c^4}T_{\mu\nu}\ . \quad (14.6)$$

Here $R = g^{\mu\nu}R_{\mu\nu}$, $T_{\mu\nu} = g_{\mu\alpha}g_{\nu\beta}T^{\alpha\beta}$, and $T^{\mu\nu} = (2/\sqrt{g})\delta\mathcal{L}_{\mathrm{SM}}/\delta g_{\mu\nu}$ is the (symmetric) energy-momentum tensor of the Standard Model matter. The theory is invariant under arbitrary coordinate transformations: $x'^\mu = f^\mu(x^\nu)$. To solve the field equations Eq. (14.6) one needs to fix this coordinate gauge freedom. E.g. the "harmonic gauge" (which is the analogue of the Lorentz gauge, $\partial_\mu A^\mu = 0$, in electromagnetism) corresponds to imposing the condition $\partial_\nu(\sqrt{g}g^{\mu\nu}) = 0$.

In this *Review*, we only consider the classical limit of gravitation (*i.e.* classical matter and classical gravity). Considering quantum matter in a classical gravitational background already poses interesting challenges, notably the possibility that the zero-point fluctuations of the matter fields generate a nonvanishing vacuum energy density ρ_{vac}, corresponding to a term $-\sqrt{g}\,\rho_{\mathrm{vac}}$ in $\mathcal{L}_{\mathrm{SM}}$ [3]. This is equivalent to adding a "cosmological constant" term $+\Lambda\, g_{\mu\nu}$ on the left-hand side of Einstein's equations Eq. (14.6), with $\Lambda = 8\pi G_N\,\rho_{\mathrm{vac}}/c^4$. Cosmological observations set bounds on Λ (see "Astrophysical Constants," Sec. 2 of this *Review*) which, when translated in particle physics units, appear suspiciously small: $\rho_{\mathrm{vac}} \lesssim 10^{-46}$ GeV^4. This bound shows that ρ_{vac}, even if it is not strictly zero, has a negligible effect on the tests discussed below. Quantizing the gravitational field itself poses a very difficult challenge because of the perturbative non-renormalizability of Einstein's Lagrangian. Supergravity and superstring theory offer promising avenues toward solving this challenge.

14.1. Experimental tests of the coupling between matter and gravity

The universality of the coupling between $g_{\mu\nu}$ and the Standard Model matter postulated in Eq. (14.5) ("Equivalence Principle") has many observable consequences. First, it predicts that the outcome of a local non-gravitational experiment, referred to local standards, does not depend on where, when, and in which locally inertial frame, the experiment is performed. This means, for instance, that local experiments should neither feel the cosmological evolution of the universe (constancy of the "constants"), nor exhibit preferred directions in spacetime (isotropy of space, local Lorentz invariance). These predictions are consistent with many experiments and observations. The best limit on a possible time variation of the basic coupling constants concerns the fine-structure constant α_{em} and has been obtained by analyzing a natural fission reactor phenomenon which took place at Oklo, Gabon, two billion years ago [4]

$$-6.7\times10^{-17}\mathrm{yr}^{-1} < \frac{\dot{\alpha}_{\mathrm{em}}}{\alpha_{\mathrm{em}}} < 5.0\times10^{-17}\mathrm{yr}^{-1}\ . \quad (14.7)$$

The highest precision tests of the isotropy of space have been performed by looking to possible quadrupolar shifts of nuclear energy levels [5]. The (null) results can be interpreted as testing the fact that the various pieces in the matter Lagrangian Eq. (14.5) are indeed coupled to one and the same external metric $g_{\mu\nu}$ to the 10^{-27} level.

The universal coupling to $g_{\mu\nu}$ postulated in Eq. (14.5) implies that two (electrically neutral) test bodies dropped at the same location and with the same velocity in an external gravitational field fall in the same way, independently of their masses and compositions. The universality of the acceleration of free fall has been verified at the 10^{-12} level both for laboratory bodies [6],

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{BeCu}} = (-1.9\pm2.5)\times10^{-12}\ , \quad (14.8)$$

and for the gravitational accelerations of the Moon and the Earth toward the Sun [7],

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{MoonEarth}} = (-3.2\pm4.6)\times10^{-13}\ . \quad (14.9)$$

Finally, Eq. (14.5) also implies that two identically constructed clocks located at two different positions in a static external Newtonian potential $U(\boldsymbol{x}) = \sum G_N m/r$ exhibit, when intercompared by means of electromagnetic signals, the (apparent) difference in clock rate,

$$\frac{\tau_1}{\tau_2} = \frac{\nu_2}{\nu_1} = 1 + \frac{1}{c^2}[U(\boldsymbol{x}_1) - U(\boldsymbol{x}_2)] + O\left(\frac{1}{c^4}\right)\ , \quad (14.10)$$

independently of their nature and constitution. This universal gravitational redshift of clock rates has been verified at the 10^{-4} level by comparing a hydrogen-maser clock flying on a rocket up to an altitude $\sim 10,000$ km to a similar clock on the ground [8]. For more details and references on experimental gravity see, *e.g.*, Refs. 9 and 10.

14.2. Tests of the dynamics of the gravitational field in the weak field regime

The effect on matter of one-graviton exchange, *i.e.* the interaction Lagrangian obtained when solving Einstein's field equations Eq. (14.6) written in, say, the harmonic gauge at first order in $h_{\mu\nu}$,

$$\Box h_{\mu\nu} = -\frac{16\pi G_N}{c^4}(T_{\mu\nu} - \tfrac{1}{2}T\eta_{\mu\nu}) + O(h^2) + O(hT) \ , \tag{14.11}$$

reads $-(8\pi G_N/c^4)T^{\mu\nu}\Box^{-1}(T_{\mu\nu} - \frac{1}{2}T\eta_{\mu\nu})$. For a system of N moving point masses, with free Lagrangian $L^{(1)} = \sum_{A=1}^{N} - m_A c^2 \sqrt{1 - \boldsymbol{v}_A^2/c^2}$, this interaction, expanded to order v^2/c^2, reads (with $r_{AB} \equiv |\boldsymbol{x}_A - \boldsymbol{x}_B|$, $\boldsymbol{n}_{AB} \equiv (\boldsymbol{x}_A - \boldsymbol{x}_B)/r_{AB}$)

$$\begin{aligned} L^{(2)} = &\frac{1}{2} \sum_{A \neq B} \frac{G_N m_A m_B}{r_{AB}} \left[1 + \frac{3}{2c^2}(\boldsymbol{v}_A^2 + \boldsymbol{v}_B^2) - \frac{7}{2c^2}(\boldsymbol{v}_A \cdot \boldsymbol{v}_B) \right. \\ &\left. - \frac{1}{2c^2}(\boldsymbol{n}_{AB} \cdot \boldsymbol{v}_A)(\boldsymbol{n}_{AB} \cdot \boldsymbol{v}_B) + O\left(\frac{1}{c^4}\right)\right] . \end{aligned} \tag{14.12}$$

The two-body interactions Eq. (14.12) exhibit v^2/c^2 corrections to Newton's $1/r$ potential induced by spin-2 exchange. Consistency at the "post-Newtonian" level $v^2/c^2 \sim G_N m/rc^2$ requires that one also considers the three-body interactions induced by some of the three-graviton vertices and other nonlinearities (terms $O(h^2)$ and $O(hT)$ in Eq. (14.11)),

$$L^{(3)} = - \sum_{B \neq A \neq C} \frac{G_N^2 m_A m_B m_C}{r_{AB} r_{AC} c^2} + O\left(\frac{1}{c^4}\right) . \tag{14.13}$$

All currently performed gravitational experiments in the solar system, including perihelion advances of planetary orbits, the bending and delay of electromagnetic signals passing near the Sun, and very accurate ranging data to the Moon obtained by laser echoes, are compatible with the post-Newtonian results Eqs. (14.11)–(14.13).

Similarly to what is done in discussions of precision electroweak experiments (see Section 10 in this *Review*), it is useful to quantify the significance of precision gravitational experiments by parameterizing plausible deviations from General Relativity. Endowing the spin-2 excitations with a (Pauli-Fierz) mass term is excluded both for phenomenological (discontinuities in observable predictions [11]) and theoretical (no energy lower bound [12]) reasons. Therefore, deviations from Einstein's pure spin-2 theory are defined by adding new, bosonic, ultra light or massless, macroscopically coupled fields. The addition of a vector (spin 1) field necessarily leads to violations of the universality of free fall and is constrained by "fifth force" experiments. See Refs. [6,13] for compilations of constraints. The addition of a scalar (spin 0) field is the most studied type of deviation from General Relativity, being motivated by many attempts to unify gravity with the Standard Model (Kaluza-Klein program, supergravity, string theory). The technically simplest class of tensor-scalar (spin 2 ⊕ spin 0) theories consists in adding a massless scalar field φ coupled to the trace of the energy-momentum tensor $T = g_{\mu\nu}T^{\mu\nu}$ [14]. The most general such theory contains an arbitrary function $a(\varphi)$ of the scalar field, and can be defined by the Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{tot}}[g_{\mu\nu}, \varphi, \psi, A_\mu, H] = &\frac{c^4}{16\pi G}\sqrt{g}(R(g) - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi) \\ &+\mathcal{L}_{\text{SM}}[\psi, A_\mu, H, \widetilde{g}_{\mu\nu}] \ , \end{aligned} \tag{14.14}$$

where G is a "bare" Newton constant, and where the Standard Model matter is coupled not to the "Einstein" (pure spin-2) metric $g_{\mu\nu}$, but to the conformally related ("Jordan-Fierz") metric $\widetilde{g}_{\mu\nu} = \exp(2a(\varphi))g_{\mu\nu}$. The scalar field equation $\Box_g\varphi = -(4\pi G/c^4)\alpha(\varphi)T$ displays $\alpha(\varphi) \equiv \partial a(\varphi)/\partial\varphi$ as the basic (field-dependent) coupling between φ and matter [15]. The one-parameter Jordan-Fierz-Brans-Dicke theory [14] is the special case $a(\varphi) = \alpha_0\varphi$ leading to a field-independent coupling $\alpha(\varphi) = \alpha_0$.

In the weak field, slow motion, limit appropriate to describing gravitational experiments in the solar system, the addition of φ modifies Einstein's predictions only through the appearance of two "post-Einstein" dimensionless parameters: $\overline{\gamma} = -2\alpha_0^2/(1 + \alpha_0^2)$ and $\overline{\beta} = +\frac{1}{2}\beta_0\alpha_0^2/(1 + \alpha_0^2)^2$, where $\alpha_0 \equiv \alpha(\varphi_0)$, $\beta_0 \equiv \partial\alpha(\varphi_0)/\partial\varphi_0$, φ_0 denoting the vacuum expectation value of φ. These parameters show up also naturally (in the form $\gamma_{\text{PPN}} = 1 + \overline{\gamma}$, $\beta_{\text{PPN}} = 1 + \overline{\beta}$) in phenomenological discussions of possible deviations from General Relativity [16,9]. The parameter $\overline{\gamma}$ measures the admixture of spin 0 to Einstein's graviton, and contributes an extra term $+\overline{\gamma}(\boldsymbol{v}_A - \boldsymbol{v}_B)^2/c^2$ in the square brackets of the two-body Lagrangian Eq. (14.12). The parameter $\overline{\beta}$ modifies the three-body interaction Eq. (14.13) by a factor $1 + 2\overline{\beta}$. Moreover, the combination $\eta \equiv 4\overline{\beta} - \overline{\gamma}$ parameterizes the lowest order effect of the self-gravity of orbiting masses by modifying the Newtonian interaction energy terms in Eq. (14.12) into $G_{AB}m_A m_B/r_{AB}$, with a body-dependent gravitational "constant" $G_{AB} = G_N[1 + \eta(E_A^{\text{grav}}/m_A c^2 + E_B^{\text{grav}}/m_B c^2) + O(1/c^4)]$, where $G_N = G\exp[2a(\varphi_0)](1+\alpha_0^2)$ and where E_A^{grav} denotes the gravitational binding energy of body A.

The best current limits on the post-Einstein parameters $\overline{\gamma}$ and $\overline{\beta}$ are (at the 68% confidence level): (i) $|\overline{\gamma}| < 2 \times 10^{-3}$ [17] deduced from the Viking mission measurement of the gravitational time delay [18] of radar signals passing near the Sun (with similar limits coming from Very Long Baseline Interferometry (VLBI) measurements of the deflection of radio waves by the Sun [19]), and (ii) $4\overline{\beta} - \overline{\gamma} = -0.0007 \pm 0.0010$ [7] from Lunar Laser Ranging measurements of a possible polarization of the Moon toward the Sun [20]. More stringent limits on $\overline{\gamma}$ are obtained in models (*e.g.*, string-inspired ones [21]) where scalar couplings violate the Equivalence Principle.

14.3. Tests of the dynamics of the gravitational field in the radiative and/or strong field regimes

The discovery of pulsars (*i.e.* rotating neutron stars emitting a beam of radio noise) in gravitationally bound orbits [22,23] has opened up an entirely new testing ground for relativistic gravity, giving us an experimental handle on the regime of radiative and/or strong gravitational fields. In these systems, the finite velocity of propagation of the gravitational interaction between the pulsar and its companion generates damping-like terms at order $(v/c)^5$ in the equations of motion [24]. These damping forces are the local counterparts of the gravitational radiation emitted at infinity by the system ("gravitational radiation reaction"). They cause the binary orbit to shrink and its orbital period P_b to decrease. The remarkable stability of the pulsar clock has allowed Taylor and collaborators to measure the corresponding very small orbital period decay $\dot{P}_b \equiv dP_b/dt \sim (v/c)^5 \sim 10^{-12}$ [23,25], thereby giving us a direct experimental confirmation of the propagation properties of the gravitational field. In addition, the surface gravitational potential of a neutron star $h_{00}(R) \simeq 2Gm/c^2R \simeq 0.4$ being a factor $\sim 10^8$ higher than the surface potential of the Earth, and a mere factor 2.5 below the black hole limit ($h_{00} = 1$), pulsar data are sensitive probes of the strong-gravitational-field regime.

Binary pulsar timing data record the times of arrival of successive electromagnetic pulses emitted by a pulsar orbiting around the center of mass of a binary system. After correcting for the Earth motion around the Sun and for the dispersion due to propagation in the interstellar plasma, the time of arrival of the Nth pulse t_N can be described by a generic, parameterized "timing formula [26]" whose functional form is common to the whole class of tensor-scalar gravitation theories:

$$t_N - t_0 = F[T_N(\nu_p, \dot{\nu}_p, \ddot{\nu}_p)\,;\, \{p^K\}\,;\, \{p^{PK}\}] \ . \tag{14.15}$$

Here, T_N is the pulsar proper time corresponding to the Nth turn given by $N/2\pi = \nu_p T_N + \frac{1}{2}\dot{\nu}_p T_N^2 + \frac{1}{6}\ddot{\nu}_p T_N^3$ (with $\nu_p \equiv 1/P_p$ the spin frequency of the pulsar, etc.), $\{p^K\} = \{P_b, T_0, e, \omega_0, x\}$ is the set of "Keplerian" parameters (notably, orbital period P_b, eccentricity e and projected semi-major axis $x = a\sin i/c$), and $\{p^{PK}\} = \{k, \gamma_{\text{timing}}, \dot{P}_b, r, s, \delta_\theta, \dot{e}, \dot{x}\}$ denotes the set of (separately measurable) "post-Keplerian" parameters. Most important among these are: the fractional periastron advance per orbit $k \equiv \dot{\omega} P_b / 2\pi$, a dimensionful time-dilation parameter γ_{timing}, the orbital period derivative $\dot{P}_b$, and the "range" and "shape" parameters of the gravitational time delay caused by the companion, r and s.

Without assuming any specific theory of gravity, one can phenomenologically analyze the data from any binary pulsar by least-squares fitting the observed sequence of pulse arrival times to the timing formula Eq. (14.15). This fit yields the "measured" values of the parameters $\{\nu_p, \dot{\nu}_p, \ddot{\nu}_p\}$, $\{p^K\}$, $\{p^{PK}\}$. Now, each specific relativistic theory of gravity predicts that, for instance, k, γ_{timing}, $\dot{P}_b$, r and s (to quote parameters that have been successfully measured from some binary pulsar data) are some theory-dependent functions of the Keplerian parameters and of the (unknown) masses m_1, m_2 of the pulsar and its companion. For instance, in General Relativity, one finds (with $M \equiv m_1 + m_2$, $n \equiv 2\pi / P_b$)

$$\begin{aligned}
k^{\text{GR}}(m_1, m_2) =& 3(1-e^2)^{-1}(G_N M n / c^3)^{2/3} , \\
\gamma^{\text{GR}}_{\text{timing}}(m_1, m_2) =& e n^{-1} (G_N M n / c^3)^{2/3} m_2 (m_1 + 2m_2)/M^2 , \\
\dot{P}^{\text{GR}}_b(m_1, m_2) =& -(192\pi / 5c^5)(1-e^2)^{-7/2} \left(1 + \tfrac{73}{24} e^2 + \tfrac{37}{96} e^4 \right) \\
& \times (G_N M n / c^3)^{5/3} m_1 m_2 / M^2 , \\
r(m_1, m_2) =& G_N m_2 / c^3 , \\
s(m_1, m_2) =& n x (G_N M n / c^3)^{-1/3} M / m_2 . \qquad (14.16)
\end{aligned}$$

In tensor-scalar theories, each of the functions $k^{\text{theory}}(m_1, m_2)$, $\gamma^{\text{theory}}_{\text{timing}}(m_1, m_2)$, $\dot{P}^{\text{theory}}_b(m_1, m_2)$, etc is modified by quasi-static strong field effects (associated with the self-gravities of the pulsar and its companion), while the particular function $\dot{P}^{\text{theory}}_b(m_1, m_2)$ is further modified by radiative effects (associated with the spin 0 propagator) [15,27].

Let us summarize the current experimental situation. In the first discovered binary pulsar PSR1913 + 16 [22,23], it has been possible to measure with accuracy the three post-Keplerian parameters k, γ_{timing} and $\dot{P}_b$. The three equations $k^{\text{measured}} = k^{\text{theory}}(m_1, m_2)$, $\gamma^{\text{measured}}_{\text{timing}} = \gamma^{\text{theory}}_{\text{timing}}(m_1, m_2)$, $\dot{P}^{\text{measured}}_b = \dot{P}^{\text{theory}}_b(m_1, m_2)$ determine, for each given theory, three curves in the two-dimensional mass plane. This yields one (combined radiative/strong-field) test of the specified theory, according to whether the three curves meet at one point, as they should. After subtracting a small ($\sim 10^{-14}$ level in $\dot{P}^{\text{obs}}_b = (-2.422 \pm 0.006) \times 10^{-12}$), but significant, Newtonian perturbing effect caused by the Galaxy [28], one finds that General Relativity passes this $(k - \gamma_{\text{timing}} - \dot{P}_b)_{1913+16}$ test with complete success at the 10^{-3} level [23,25]

$$\begin{aligned}
\left[\frac{\dot{P}^{\text{obs}}_b - \dot{P}^{\text{galactic}}_b}{\dot{P}^{\text{GR}}_b [k^{\text{obs}}, \gamma^{\text{obs}}_{\text{timing}}]} \right]_{1913+16} &= 1.0032 \pm 0.0023(\text{obs}) \pm 0.0026(\text{galactic}) \\
&= 1.0032 \pm 0.0035 . \qquad (14.17)
\end{aligned}$$

Here $\dot{P}^{\text{GR}}_b [k^{\text{obs}}, \gamma^{\text{obs}}_{\text{timing}}]$ is the result of inserting in $\dot{P}^{\text{GR}}_b(m_1, m_2)$ the values of the masses predicted by the two equations $k^{\text{obs}} = k^{\text{GR}}(m_1, m_2)$, $\gamma^{\text{obs}}_{\text{timing}} = \gamma^{\text{GR}}_{\text{timing}}(m_1, m_2)$. This experimental evidence for the reality of gravitational radiation damping forces at the 0.3% level is illustrated in Fig. 14.1, which shows actual orbital phase data (after subtraction of a linear drift).

The discovery of the binary pulsar PSR1534 + 12 [29] has allowed one to measure the four post-Keplerian parameters k, γ_{timing}, r and s, and thereby to obtain two (four observables minus two masses) tests of strong field gravity, without mixing of radiative effects [30]. General Relativity passes these tests within the measurement accuracy [30,23]. The most precise of these new, pure, strong-field tests is the one obtained by combining the measurements of k, γ, and s. Using the data reported in [31], one finds agreement at the 1% level:

$$\left[\frac{s^{\text{obs}}}{s^{\text{GR}}[k^{\text{obs}}, \gamma^{\text{obs}}_{\text{timing}}]} \right]_{1534+12} = 1.010 \pm 0.008 . \qquad (14.18)$$

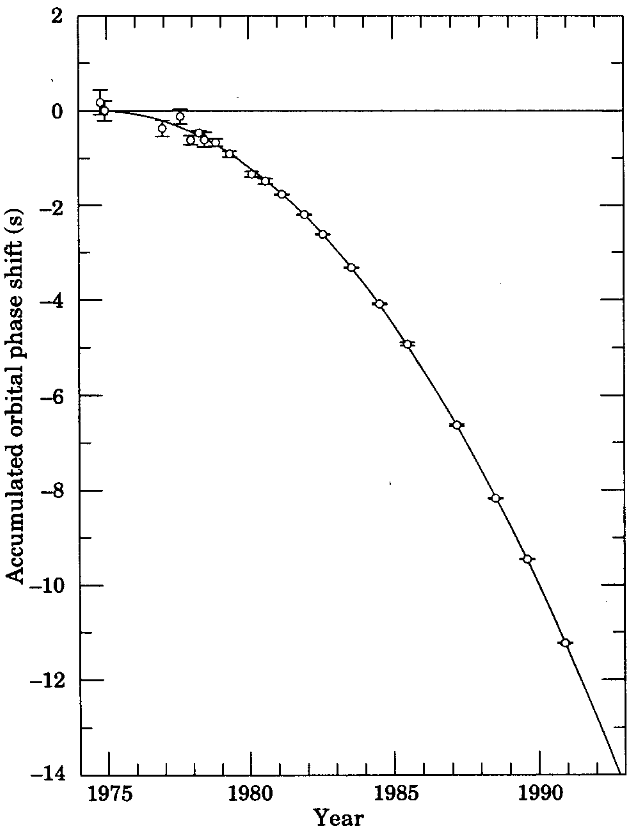

Figure 14.1: Accumulated shift of the times of periastron passage in the PSR 1913+16 system, relative to an assumed orbit with a constant period. The parabolic curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces. (Figure obtained with permission from Ref. 23.)

Recently, it has been possible to measure the orbital period change of PSR1534 + 12. General Relativity passes the corresponding $(k - \gamma_{\text{timing}} - \dot{P}_b)_{1534+12}$ test with success at the 15% level [32].

Several other binary pulsar systems, of a nonsymmetric type (nearly circular systems made of a neutron star and a white dwarf), can also be used to test relativistic gravity [33,34]. The constraints on tensor-scalar theories provided by three binary-pulsar "experiments" have been analyzed in [27] and shown to exclude a large portion of the parameter space allowed by solar-system tests.

The tests considered above have examined the gravitational interaction on scales between a few centimeters and a few astronomical units. Millimeter scale tests of Newtonian gravity have been reported in Ref. 35. On the other hand, the general relativistic action on light and matter of an external gravitational field on a length scale ~ 100 kpc has been verified to $\sim 30\%$ in some gravitational lensing systems (see, *e.g.*, [36]). Some tests on cosmological scales are also available. In particular, Big Bang Nucleosynthesis (see Section 15 of this *Review*) has been used to set significant constraints on the variability of the gravitational "constant" [37].

14.4. Conclusions

All present experimental tests are compatible with the predictions of the current "standard" theory of gravitation: Einstein's General Relativity. The universality of the coupling between matter and gravity (Equivalence Principle) has been verified at the 10^{-12} level. Solar system experiments have tested the weak-field predictions of Einstein's theory at the 10^{-3} level. The propagation properties of relativistic gravity, as well as several of its strong-field aspects, have been verified at the 10^{-3} level in binary pulsar experiments. Several important new developments in experimental gravitation are expected in the near future. The approved NASA Gravity Probe B mission (a space gyroscope experiment; due for launch in 2000) will directly measure the gravitational spin-orbit and spin-spin couplings, thereby measuring the weak-field post-Einstein parameter $\bar{\gamma}$ to the 10^{-5} level (an improvement by two orders of magnitude). The planned NASA-ESA MiniSTEP mission (a satellite test of the Equivalence Principle) should test the universality of acceleration of free fall down to the 10^{-18} level (an improvement by six orders of magnitude). Finally, the various kilometer-size laser interferometers under construction (notably LIGO in the USA and VIRGO in Europe) should, soon after 2000, directly detect gravitational waves arriving on Earth. As the sources of these waves are expected to be extremely relativistic objects with strong internal gravitational fields (*e.g.*, coalescing binary neutron stars, or neutron stars plunging into large black holes), their detection will allow one to experimentally probe gravity in highly dynamical circumstances.

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15. BIG-BANG COSMOLOGY

Revised April 1998 by K.A. Olive (University of Minnesota).

At early times, and today on a sufficiently large scale, our Universe is very nearly homogeneous and isotropic. The most general space-time metric for a homogeneous, isotropic space is the Friedmann-Robertson-Walker metric (with $c = 1$) [1,2,3]:

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right] . \qquad (15.1)$$

$R(t)$ is a scale factor for distances in comoving coordinates. With appropriate rescaling of the corrdinates, κ can be chosen to be $+1$, -1, or 0, corresponding to closed, open, or spatially flat geometries. Einstein's equations lead to the Friedmann equation

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\, G_N\, \rho}{3} - \frac{\kappa}{R^2} + \frac{\Lambda}{3} , \qquad (15.2)$$

as well as to

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}\,(\rho + 3p) , \qquad (15.3)$$

where $H(t)$ is the Hubble parameter, ρ is the total mass-energy density, p is the isotropic pressure, and Λ is the cosmological constant. (For limits on Λ, see the Table of Astrophysical Constants; we will assume here $\Lambda = 0$.) The Friedmann equation serves to define the density parameter Ω_0 (subscript 0 indicates present-day values):

$$\kappa/R_0^2 = H_0^2(\Omega_0 - 1) , \qquad \Omega_0 = \rho_0/\rho_c ; \qquad (15.4)$$

and the critical density is defined as

$$\rho_c \equiv \frac{3H^2}{8\pi\, G_N} = 1.88 \times 10^{-29}\, h^2 \text{ g cm}^{-3} , \qquad (15.5)$$

with

$$H_0 = 100\, h_0 \text{ km s}^{-1} \text{ Mpc}^{-1} = h_0/(9.78 \text{ Gyr}) . \qquad (15.6)$$

Observational bounds give $0.4 < h_0 < 1$. The three curvature signatures $\kappa = +1, -1$, and 0 correspond to $\Omega_0 > 1$, < 1, and $= 1$. Knowledge of Ω_0 is even poorer than that of h_0. Luminous matter (stars and associated material) contribute $\Omega_{\text{lum}} \leq 0.01$. There is no lack of evidence for copious amounts of dark matter: rotation curves of spiral galaxies, virial estimates of cluster masses, gravitational lensing by clusters and individual galaxies, and so on. The minimum amount of dark matter required to explain the flat rotation curves of spiral galaxies only amounts to $\Omega_0 \sim 0.1$, while estimates for Ω_0 based upon cluster virial masses suggests $\Omega_0 \sim 0.2 - 0.4$. The highest estimates for the mass density come from studies of the peculiar motions of galaxies (including our own); estimates for Ω_0 obtained by relating peculiar velocity measurements to the distribution galaxies within a few hundred Mpc approach unity. A conservative range for the mass density is: $0.1 \leq \Omega_0 \leq 2$. The excess of Ω_0 over Ω_{lum} leads to the inference that most of the matter in the Universe is nonluminous dark matter.

In an expanding universe, the wavelength of light emitted from a distant source is shifted towards the red. The redshift z is defined such that $1 + z$ is the ratio of the detected wavelength (λ) to emitted (laboratory) wavelength (λ_e) of some electromagnetic spectral feature. It follows from the metric given in Eq. (15.1) that

$$1 + z = \lambda/\lambda_e = R_0/R_e \qquad (15.7)$$

where R_e is the value of the scale factor at the time the light was emitted. For light emitted in the not too distant past, one can expand R_e and write $R_e \simeq R_0 + (t_e - t_0)\dot{R}_0$. For small (compared to H_0^{-1}) $\Delta t = (t_e - t_0)$, Eq. (15.7) takes the form of Hubble's law

$$z \approx \Delta t \frac{\dot{R}_0}{R_0} \approx \ell H_0 , \qquad (15.8)$$

where ℓ is the distance to the source.

Energy conservation implies that

$$\dot{\rho} = -3(\dot{R}/R)(\rho + p) , \qquad (15.9)$$

so that for a matter-dominated ($p = 0$) universe $\rho \propto R^{-3}$, while for a radiation-dominated ($p = \rho/3$) universe $\rho \propto R^{-4}$. Thus the less singular curvature term κ/R^2 in the Friedmann equation can be neglected at early times when R is small. If the Universe expands adiabatically, the entropy per comoving volume ($\equiv R^3 s$) is constant, where the entropy density is $s = (\rho + p)/T$ and T is temperature. The energy density of radiation can be expressed (with $\hbar = c = 1$) as

$$\rho_r = \frac{\pi^2}{30} N(T)(kT)^4 , \qquad (15.10)$$

where $N(T)$ counts the effectively massless degrees of freedom of bosons and fermions:

$$N(T) = \sum_B g_B + \frac{7}{8}\sum_F g_F . \qquad (15.11)$$

For example, for $m_\mu > kT > m_e$, $N(T) = g_\gamma + 7/8\,(g_e + 3g_\nu) = 2 + 7/8\,[4 + 3(2)] = 43/4$. For $m_\pi > kT > m_\mu$, $N(T) = 57/4$. At temperatures less than about 1 MeV, neutrinos have decoupled from the thermal background, *i.e.*, the weak interaction rates are no longer fast enough compared with the expansion rate to keep neutrinos in equilibrium with the remaining thermal bath consisting of $\gamma, e^\pm$. Furthermore, at temperatures $kT < m_e$, by entropy conservation, the ratio of the neutrino temperature to the photon temperature is given by $(T_\nu/T_\gamma)^3 = g_\gamma/(g_\gamma + \frac{7}{8}g_e) = 4/11$.

In the early Universe when $\rho \approx \rho_r$, then $\dot{R} \propto 1/R$, so that $R \propto t^{1/2}$ and $Ht \rightarrow 1/2$ as $t \rightarrow 0$. The time-temperature relationship at very early times can then be found from the above equations:

$$t = \frac{2.42}{\sqrt{N(T)}}\left(\frac{1 \text{ MeV}}{kT}\right)^2 \text{ sec} . \qquad (15.12)$$

At later times, since the energy density in radiation falls off as R^{-4} and the energy density in non-relativistic matter falls off as R^{-3}, the Universe eventually became matter dominated. The epoch of matter-radiation density equality is determined by equating the matter density at t_{eq}, $\rho_m = \Omega_0\rho_c(R_0/R_{\text{eq}})^3$ to the radiation density, $\rho_r = (\pi^2/30)[2 + (21/4)(4/11)^{4/3}](kT_0)^4(R_0/R_{\text{eq}})^4$ where T_0 is the present temperature of the microwave background (see below). Solving for $(R_0/R_{\text{eq}}) = 1 + z_{\text{eq}}$ gives

$$\begin{aligned} z_{\text{eq}} + 1 &= \Omega_0 h_0^2/4.2 \times 10^{-5} = 2.4 \times 10^4\, \Omega_0 h_0^2 ; \\ kT_{\text{eq}} &= 5.6\, \Omega_0 h_0^2 \text{ eV} ; \\ t_{\text{eq}} &\approx 0.39(\Omega_0 H_0^2)^{-1/2}(1 + z_{\text{eq}})^{-3/2} \\ &= 3.2 \times 10^{10}(\Omega_0 h_0^2)^{-2} \text{ sec} . \end{aligned} \qquad (15.13)$$

Prior to this epoch the density was dominated by radiation (relativistic particles; see Eq. (15.10)), and at later epochs matter density dominated. Atoms formed at $z \approx 1300$, and by $z_{\text{dec}} \approx 1100$ the free electron density was low enough that space became essentially transparent to photons and matter and radiation were decoupled. These are the photons observed in the microwave background today.

The age of the Universe today, t_0, is related to both the Hubble parameter and the value of Ω_0 (still assuming that $\Lambda = 0$). In the Standard Model, $t_0 \gg t_{\text{eq}}$ and we can write

$$t_0 = H_0^{-1}\int_0^1 \left(1 - \Omega_0 + \Omega_0 x^{-1}\right)^{-1/2} dx . \qquad (15.14)$$

Constraints on t_0 yield constraints on the combination $\Omega_0 h_0^2$. For example, $t_0 \geq 13 \times 10^9$ yr implies that $\Omega_0 h_0^2 \leq 0.25$ for $h_0 \geq 0.5$, or $\Omega_0 h_0^2 \leq 0.45$ for $h_0 \geq 0.4$, while $t_0 \geq 10 \times 10^9$ yr implies that $\Omega_0 h_0^2 \leq 0.8$ for $h_0 \geq 0.5$, or $\Omega_0 h_0^2 \leq 1.1$ for $h_0 \geq 0.4$.

The present temperature of the microwave background is $T_0 = 2.728 \pm 0.002$ K as measured by COBE [4], and the number density of photons $n_\gamma = (2\zeta(3)/\pi^2)(kT_0)^3 \approx 412\ \mathrm{cm}^{-3}$. The energy density in photons (for which $g_\gamma = 2$) is $\rho_\gamma = (\pi^2/15)(kT_0)^4$. At the present epoch, $\rho_\gamma = 4.66 \times 10^{-34}\ \mathrm{g\ cm}^{-3} = 0.262\ \mathrm{eV\ cm}^{-3}$. For nonrelativistic matter (such as baryons) today, the energy density is $\rho_B = m_B n_B$ with $n_B \propto R^{-3}$, so that for most of the history of the Universe n_B/s is constant. Today, the entropy density is related to the photon density by $s = (4/3)(\pi^2/30)[2 + (21/4)(4/11)](kT_0)^3 = 7.0\,n_\gamma$. Big Bang nucleosynthesis calculations limit $\eta = n_B/n_\gamma$ to $2.8 \times 10^{-10} \leq \eta \leq 4.0 \times 10^{-10}$. The parameter η is also related to the portion of Ω in baryons

$$\Omega_B = 3.67 \times 10^7 \eta\, h_0^{-2}\, (T_0/2.728\ \mathrm{K})^3\ , \tag{15.15}$$

so that $0.010 < \Omega_B\, h_0^2 < 0.015$, and hence the Universe cannot be closed by baryons.

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16. BIG-BANG NUCLEOSYNTHESIS

Revised July 1997 by K.A. Olive (Univ. of Minnesota) and D.N. Schramm (deceased).

Among the successes of the standard big-bang model is the agreement between the predictions of big-bang nucleosynthesis (BBN) for the abundances of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, and the primordial abundances inferred from observational data (see [1–3] for a more complete discussion). These abundances span some nine orders of magnitude: ^{4}He has an abundance by number relative to hydrogen of about 0.08 (accounting for about 25% of the baryonic mass), while ^{7}Li, the least abundant of the elements with a big-bang origin, has a abundance by number relative to hydrogen of about $\sim 10^{-10}$.

16.1. Big-bang nucleosynthesis theory

The BBN theory matches the observationally determined abundances with a single well-defined parameter, the baryon-to-photon ratio, η. All the light-element abundances can be explained with η in the range $(1.5–6.3) \times 10^{-10}$, or $\eta_{10} \equiv \eta \times 10^{10} = 1.5–6.3$. Equivalently, this range can be expressed as the allowed range for the baryon mass density, $\rho_B = 1.0–4.3 \times 10^{-31}$ g cm^{-3}, and can be converted to the fraction, Ω, of the critical density, ρ_c.

The synthesis of the light elements was affected by conditions in the early Universe at temperatures $T \lesssim 1$ MeV, corresponding to an age as early as 1 s. At somewhat higher temperatures, weak-interaction rates were in equilibrium, thus fixing the ratio of the neutron and proton number densities. At $T \gg 1$ MeV, $n/p \approx 1$, since the ratio was given approximately by the Saha relation, $n/p \approx e^{-Q/T}$, where Q is the neutron-proton mass difference. As the temperature fell, the Universe approached the point ("freeze-out") where the weak-interaction rates were no longer fast enough to maintain equilibrium. The final abundance of ^{4}He is very sensitive to the n/p ratio at freeze-out.

The nucleosynthesis chain begins with the formation of deuterium in the process $pn \rightarrow D\gamma$. However, photo-dissociation by the high number density of photons ($n_\gamma/n_B = \eta^{-1} \sim 10^{10}$) delays production of deuterium (and other complex nuclei) well past the point where T reaches the binding energy of deuterium, $E_B = 2.2$ MeV. (The average photon energy in a blackbody is $\overline{E}_\gamma \approx 2.7\ T$.) When the quantity $\eta^{-1}\exp(-E_B/T)$ reaches about 1 (at $T \approx 0.1$ MeV), the photo-dissociation rate finally falls below the nuclear production rate.

The 25% fraction of mass in ^{4}He due to BBN is easily estimated by counting the number of neutrons present when nucleosynthesis begins. When the weak-interaction rates freeze-out at about $T \approx 0.8$ MeV, the n-to-p ratio is about 1/6. When free-neutron decays prior to deuterium formation are taken into account, the ratio drops to $n/p \lesssim 1/7$. Then simple counting yields a primordial ^{4}He mass fraction

$$Y_p = \frac{2(n/p)}{1 + n/p} \lesssim 0.25\ . \tag{16.1}$$

In the Standard Model, the ^{4}He mass fraction depends primarily on the baryon-to-photon ratio η, as it is this quantity that determines when nucleosynthesis via deuterium production may begin. But because the n/p ratio depends only weakly on η, the ^{4}He mass fraction is relatively flat as a function of η. The effect of the uncertainty in the neutron half-life, $\tau_n = 887 \pm 2$ s, is now small. Lesser amounts of the other light elements are produced: D and ^{3}He at the level of a few times 10^{-5} by number relative to H, and ^{7}Li/H at the level of about 10^{-10}, when η is in the range $1–10 \times 10^{-10}$.

When we go beyond the Standard Model, the ^{4}He abundance is very sensitive to changes in the expansion rate, which can be related to the effective number of neutrino flavors. This will be discussed below.

The calculated abundances of the light elements are shown in Fig. 16.1 as a function of η_{10}. The curves for the ^{4}He mass fraction, Y_p, bracket the range based on the uncertainty of the neutron mean-life, $\tau_n = 887 \pm 2$ s. The spread in the ^{7}Li curves is due to the 1σ uncertainties in nuclear cross sections leading to ^{7}Li and ^{7}Be which subsequently decays to ^{7}Li [4–6]. The uncertainties in the D and ^{3}He predictions are small and have been neglected here. The boxes show the observed abundances with their range of uncertainty, discussed below. Since the observational boxes line up on top of each other, there is an overall agreement between theory and observations for η_{10} in the range 1.5–6.3.

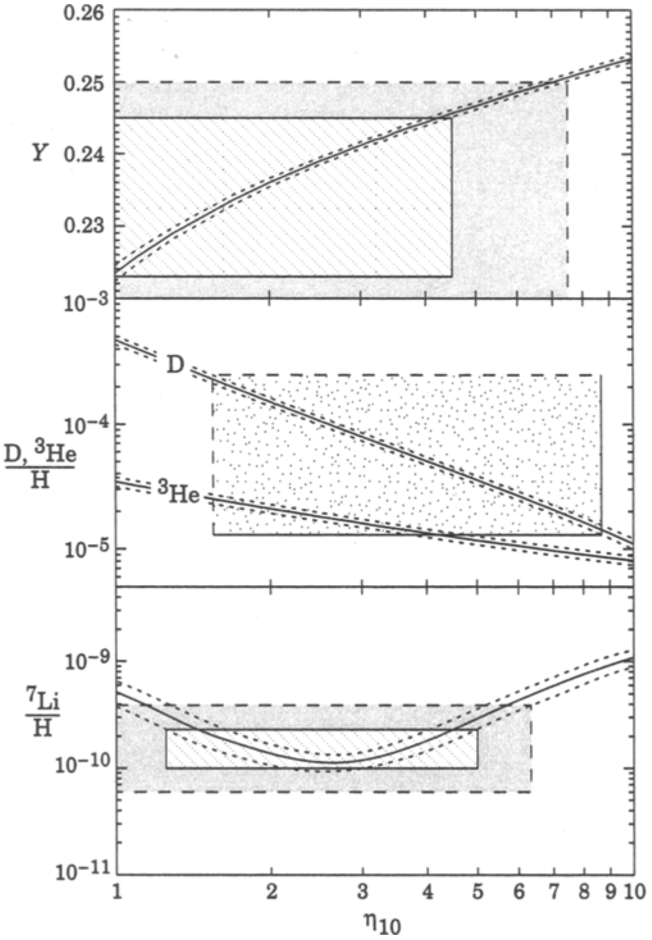

Figure 16.1: The abundances of D, ^{3}He, ^{4}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Also shown by a series of boxes is the comparison between these predictions and the observational determination of the light element abundances. See text for details.

16.2. Observations

Because stars produce helium as well as heavier elements, one must search for primordial helium in regions where stellar processing has been minimal, *i.e.*, in regions where abundances of elements such as carbon, nitrogen and oxygen are very low. There are extensive compilations of observed abundances of ^{4}He, N, and O in many different extra-galactic regions of ionized H [7–9]. Extrapolating the ^{4}He abundances from the data leads to a observational estimate for Y_p of [10–12]

$$Y_p = 0.234 \pm 0.002 \pm 0.005\ . \tag{16.2}$$

(Here and elsewhere, the first error is the statistical standard deviation, and the second systematic.) The large box in Fig. 16.1 bracketing the ^{4}He curves covers the range 0.223 to 0.245, where the half height is given as twice the errors when added in quadrature. There has been some debate on the size of systematic errors [4] and the dashed box is obtained using a larger error, allowing Y_p to take a maximal value of 0.250.

Observations for deuterium and ^{3}He abundances currently present certain difficulties. All deuterium is primordial [13], but some of the primordial deuterium has been destroyed. Thus, as can be seen in the figure, the present deuterium abundance gives us an absolute upper limit to η. However, to get more information requires either an understanding of galactic chemical evolution of deuterium or a direct measurement of primordial deuterium. Even more problematical is ^{3}He: Not only is primordial ^{3}He destroyed in stars but it is very likely that at least some low-mass stars are net producers of ^{3}He. Neither the galactic chemical evolution of ^{3}He nor the production of ^{3}He in stars is well understood with standard models and observations presenting an inconsistent picture.

It appears that D/H has decreased over the age of the galaxy. Samples obtained deep inside meteorites provide measurements of the true (pre)-solar system abundance of ^{3}He, while measurements on meteoritic near-surface samples, the solar wind, and lunar soil samples also contain ^{3}He converted from deuterium in the early pre-main-sequence stage of the sun. The best current values are [14]

$$\begin{aligned}\left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_\odot &= (4.1 \pm 1.0) \times 10^{-5} \;, \\ \left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right)_\odot &= (1.5 \pm 0.3) \times 10^{-5} \;. \end{aligned} \qquad (16.3)$$

The difference between these is the pre-solar D abundance. There has also been a recent measurement of HD in the atmosphere of Jupiter [15] yielding a value D/H = $(5 \pm 2) \times 10^{-5}$. This would be an important measurement if it can be acertained that isotopic fractionation of deuterium did not occur, however, this point is debatable at the present time.

The present interstellar-medium abundance of D/H is [16]

$$\mathrm{D/H} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5} \;. \qquad (16.4)$$

It is this lowest value of D/H that provides the most robust upper bound on η, since D is only destroyed. It is shown (decreased by twice the errors added in quadrature) as the lower right corner of the D and ^{3}He box in Fig. 16.1. Thus, with confidence we can be sure that $\eta_{10} < 9$ And correspondingly $\Omega_B h^2 < 0.033$

Deuterium has also been detected in high-redshift, low-metallicity quasar absorption systems [17–19]. These measured abundances should represent the primordial value, but they are at present not consistent: Two [17,18] give a relatively high value for D/H $\approx 2 \times 10^{-4}$ while the other [19] gives D/H $\approx 2.3 \pm 0.3 \times 10^{-5}$. Although it appears that the quality of the low D/H data is better than those showing high D/H, the latter can be used at the very least as an upper limit to primordial D/H and this is shown by the dashed box in Fig. 16.1. As one can see, the corresponding value of Y_p (at the same value of η as inferred by the observation of a high D/H) is in excellent agreement with the data. ^{7}Li is also acceptable at this value as well. However, due to the still somewhat preliminary status of this observation, it is premature to use it to fix the primordial abundance. A high value for the D abundance would require an even greater degree of D destruction over the age of the galaxy. The lower measurement for D/H requires that systematics work coherently for both ^{4}He and ^{7}Li to give an overlap with this data. Eventually, the primordial D/H issue will hopefully be resolved and give a correspondingly narrow allowed range in η and perhaps change the nature of the ^{3}He and ^{7}Li (see below) arguments which are currently dominated by galactic and/or stellar evolution issuses.

Finally, we turn to ^{7}Li. In old, hot, population-II stars, ^{7}Li is found to have a very nearly uniform abundance. For stars with a surface temperature $T > 5500$ K and a metallicity less than about 1/20th solar (so that effects such as stellar convection may not be important), the abundances show little or no dispersion beyond that consistent with the errors of individual measurements. Much data has been obtained recently from a variety of sources, and the best estimate for the mean ^{7}Li abundance and its statistical uncertainty in halo stars is [20](the estimate of the systematic uncertainty discussed below is our own)

$$\mathrm{Li/H} = (1.6 \pm 0.1^{+0.4+1.6}_{-0.3-0.5}) \times 10^{-10} \;. \qquad (16.5)$$

The first error is statistical, and the second is a systematic uncertainty that covers the range of abundances derived by various methods. The box in Fig. 16.1 corresponds to these errors (as before, with a half height of $2\sigma_{\rm stat} + \sigma_{\rm syst}$). The third set of errors in Eq. (16.5) accounts for the possibility that as much as half of the primordial ^{7}Li has been destroyed in stars, and that as much as 30% of the observed ^{7}Li was produced in cosmic ray collisions rather than in the Big Bang. These uncertainties are shown by the dashed box in Fig. 16.1. Observations of ^{6}Li, Be, and B help constrain the degree to which these effects play a role [21–23].

16.3. A consistent value for η

For the Standard Model of BBN to be deemed successful, theory and observation of the light element abundances must agree using a single value of η. We summarize the constraints on η from each of the light elements. From the ^{4}He mass fraction, $Y_p < (0.245\text{–}0.250)$, we have $\eta_{10} < (4.5\text{–}7.6)$ as a 2σ upper limit (the highest values use possible systematic errors up to their extreme range). Because of the sensitivity to the assumed upper limit on Y_p and Li/H, the upper limit on η from D/H, is still of value. From D/H $> 1.3 \times 10^{-5}$, we have $\eta_{10} \lesssim 9$.

The lower limit on η_{10} can be obtained from either D/H or ^{7}Li. From the high D/H measurement in quasar absorption systems, we obtain $\eta_{10} > 1.5$. ^{7}Li allows a broad range for η_{10} consistent with the other elements. When uncertainties in the reaction rates and systematic uncertainties in the observed abundances are both taken into account, ^{7}Li allows values of η_{10} between (1.0–6.3).

The determination of η depends on our certainty that the observations of the light elements abundances can be translated into primordial abundances. This is perhaps more straightforward for ^{4}He and ^{7}Li, where the element abundances are determined in primitive low metallicity environments. If it turns out that a consistent value for D/H can be obtained from quasar absorption systems, then because of the slope of D/H with respect to η, D/H will be the best isotopic ratio for the determination of η. Until then, the use of the D and ^{3}He abundance determinations is necessarily complicated by the evolution of the abundances of these elements over the star forming history of the galaxy. Uncertainties in the ^{3}He evolution are compounded by uncertainties of stellar production/destruction mechanisms. The resulting overall consistent range for η_{10} is extended to (1.5–6.3) when systematic errors are pushed to their limits. These bounds on η_{10} constrain the fraction of critical density in baryons, Ω_B, to be

$$0.005 < \Omega_B h_0^2 < 0.024 \qquad (16.6)$$

for a Hubble parameter, h_0, between 0.4 and 1.0. The corresponding range for Ω_B is 0.005–0.15.

Perhaps the best test of BBN will come when anisotropies in the microwave background check the determination of Ω_B. At present, other measurements (such as of hot x-ray gas in clusters of galaxies, Lyman-α clouds, or microwave anisotropies) of Ω_B give considerably larger uncertainties than those from BBN, but they are consistent with the BBN range.

16.4. Beyond the Standard Model

Limits on particle physics beyond the Standard Model come mainly from the observational bounds on the ^{4}He abundance. As discussed earlier, the neutron-to-proton ratio is fixed by its equilibrium value at the freeze-out of the weak-interaction rates at a temperature $T_f \sim 1$ MeV, with corrections for free neutron decay. Furthermore, freeze-out is determined by the competition between the weak-interaction rates and the expansion rate of the Universe,

$$G_F{}^2 T_f{}^5 \sim \Gamma_{\rm wk}(T_f) = H(T_f) \sim \sqrt{G_N N}\, T_f{}^2 \;, \qquad (16.7)$$

where N counts the total (equivalent) number of relativistic particle species. The presence of additional neutrino flavors (or of any other relativistic species) at the time of nucleosynthesis increases the energy density of the Universe and hence the expansion rate, leading to a larger value of T_f, n/p, and ultimately Y_p. It is clear that just as one can place limits [25] on N, any changes in the weak or gravitational coupling constants can be similarly constrained.

In the Standard Model, the number of particle species can be written as $N = 5.5 + \frac{7}{4}N_\nu$; 5.5 accounts for photons and $e^\pm$, and N_ν is the number of (massless) neutrino flavors. The helium curves in Fig. 16.1 were computed assuming $N_\nu = 3$, and the computed ^{4}He abundance scales roughly as $\Delta Y_{\rm BBN} \approx 0.012$–$0.014\ \Delta N_\nu$. Clearly the central value for N_ν from BBN will depend on η. If the best value for the observed primordial ^{4}He abundance is 0.234, then, for $\eta_{10} \sim 1.8$, the central value for N_ν is 3. By means of a likelihood analysis on η and N_ν based on ^{4}He and ^{7}Li [24,26], (see also [27]), it was found that the 95% CL ranges are $1.6 \leq N_\nu \leq 4.0$, and $1.3 \leq \eta_{10} \leq 5.0$.

The limits on N_ν can be translated into limits on other types of particles or particle masses that would affect the expansion rate of the Universe just prior to nucleosynthesis. In some cases, it is the interaction strengths of new particles which are constrained. Particles with less than full weak strength interactions contribute less to the energy density than particles that remain in equilibrium up to the time of nucleosynthesis [28].

We close with a simple example. Suppose there exist three right-handed neutrinos with only right-handed interactions of strength $G_R < G_F$. The standard left-handed neutrinos are no longer in equilibrium at temperatures below ~ 1 MeV. Particles with weaker interactions decouple at higher temperatures, and their number density ($\propto T^3$) relative to neutrinos is reduced by the annihilations of particles more massive than 1 MeV. If we use the upper bound $N_\nu < 4.0$, then the three right-handed neutrinos must have a temperature $3(T_{\nu_R}/T_{\nu_L})^4 < 1$. Since the temperature of the decoupled ν_R's is determined by entropy conservation, $T_{\nu_R}/T_{\nu_L} = [(43/4)/N(T_f)]^{1/3} < 0.76$, where T_f is the freeze-out temperature of the ν_R's. Thus $N(T_f) > 24$ and decoupling must have occurred at $T_f > 140$ MeV. Finally, the decoupling temperature is related to G_R by $(G_R/G_F)^2 \sim (T_f/3\ \text{MeV})^{-3}$, where 3 MeV corresponds to the decoupling temperature for ν_L. This yields a limit $G_R \lesssim 10^{-2}\ G_F$. These limits are strongly dependent on the assumed upper limit to N_ν; for $N_\nu < 3.5$, the limit on G_R strengthened to $G_R < 0.002\ G_F$, since T_f is constrained to be larger than the temperature corresponding to the QCD transition in the early Universe.

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17. THE HUBBLE CONSTANT

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In a uniform expanding universe, the position $\boldsymbol{r}$ and velocity $\boldsymbol{v}$ of any particle relative to another obey Hubble's relation $\boldsymbol{v} = H_0 \boldsymbol{r}$, where H_0 is Hubble's constant.[*] As cosmological distances are measured in Mpc, the natural unit for H_0 is km s^{-1} Mpc^{-1}, which has the dimensions of inverse time: $[100 \text{ km s}^{-1} \text{ Mpc}^{-1}]^{-1} = 9.78 \times 10^9$ yr.

The real universe is nonuniform on small scales, and its motion obeys the Hubble relation only as a large scale average. As typical non-Hubble motions ("peculiar velocities") are less than about 500 km s^{-1}, on scales more than about 5,000 km s^{-1} the deviations from Hubble flow are less than about 10%, so the notion of a global Hubble constant is well defined. The value of H_0 averaged over the local 15,000 km s^{-1} volume is known to lie within 10% of its global value even if H_0 itself is not known this precisely [1–3].

Measurement of H_0 thus entails measuring large absolute distances. Traditionally, certain astronomical systems ("Standard Candles") are used to measure relative distance, and are tied to an absolute trigonometric parallax scale by a series of distance ratios (or "distance ladder") [4-9]. Several relatively new techniques now allow direct absolute calibration using physical models.

Table 17.1 lists several candles and calibrators with a typical range of distance accessible to each. The ranges are not precisely defined; the near end suffers from small numbers of accessible objects and the far end from faint signal. The precision quoted is in units of astronomical "distance modulus," given by $\mu = 5\log_{10}(\textit{distance in parsecs}) - 5.0$; a ± 0.1 magnitude error in magnitude or distance modulus corresponds to a 5% error in distance. In the case of distance ratios the precision is estimated by cross-checking indicators on a galaxy-by-galaxy basis. Some options often used for verification and absolute calibration are listed. The Hubble relation itself is included, as it is the most precise indication of relative distance for large distances, and is used to verify the standardization of several candles.

Table 17.1: Selected extragalactic distance indicators.[†]

Technique	Range of distance	Accuracy (1σ)	Verification/ calibration
Cepheids	<LMC to 25 Mpc	0.15 mag	LMC/parallax
SNIa	4 Mpc to > 2 Gpc	0.2 mag	Hubble/Cepheid
EPM/SNII	LMC to 200 Mpc	0.4 mag	Hubble/Cepheid
PNLF	LMC to 20 Mpc	0.1 mag	SBF/Cepheid
SBF	1 Mpc to 100 Mpc	0.1 mag	PNLF/Cepheid
TF	1 Mpc to 100 Mpc	0.3 mag	Hubble/Cepheid
BCG	50 Mpc to 1 Gpc	0.3 mag	Hubble/SBF
GCLF	1 Mpc to 100 Mpc	0.4 mag	SBF/MWG
SZ	100 Mpc to > 1 Gpc	0.4 mag	Hubble/Model
GL	~5 Gpc	0.4 mag	Model
Hubble	20 Mpc to $\gtrsim$1Gpc	500 km s^{-1} $\div\ H_0 D$	BCG, SNeIa/H_0

MWG = Milky Way Galaxy

[†] Extracted from [4-9].

17.1. Calibration of Cepheid variables

Using stars as standard candles and the Earth's orbit as a baseline, distances in the nearby Galaxy are tied directly to trigonometric parallax measurements. With the release in 1997 of the first results of the Hipparcos satellite, the range, precision, and size of calibrating samples have greatly improved. The early recalibrations of the absolute scale of the Galaxy indicate an increase in the distance scale for Cepheid variables which propagates to all larger scale measurements, reducing previous measurements of H_0 by 0.1 to 0.2 mag [10,11]. (Note that the RRLyrae distance scale, used to calibrate the distances to old globular clusters within the Galaxy, has also increased [12], which increases the stellar brightness and decreases their estimated age, possibly reconciling the cosmic age and Hubble parameter for a wider range of cosmological models [11,13].) The revised distance scale however would also increase the distance to the Large Magellanic Cloud (LMC) which is constrained by geometrical arguments from SN 1987A [14]. Another promising method is based on detailed knowledge of orbits of gas in N4258 precisely constrained by observations of maser gas emission. This has the potential to calibrate the Cepheid scale independently [23].

The best studied and most trusted of the absolute calibrators, Cepheids are bright stars undergoing overstable oscillations driven by the variation of helium opacity with temperature. The period of oscillation is tightly correlated with the absolute brightness of the star, though this "period-luminosity relation" [15] may vary with metallicity [16,17]. With Hubble Space Telescope (HST), Cepheids are now measured in over a dozen galaxies out to 25 Mpc ($\mu = 32$) allowing direct absolute calibration of many other indicators to better than 10% accuracy [18–22].

17.2. Type Ia supernovae (SNIa)

A SNIa occurs when a degenerate dwarf, of the order of a solar mass and of CNO composition, undergoes explosive detonation or deflagration by nuclear burning to iron-group elements (Ni, Co, Fe). Their uniformity arises because the degenerate material only becomes unstable when it is gravitationally compressed to where the electrons become close to relativistic, which requires approximately a Chandrasekhar mass (1.4 solar masses). Theoretical models of the explosion predict approximately the right peak brightness, but cannot give a precise calibration. SNIa are very bright, so their brightness distribution can be studied using the distant Hubble flow as a reference. Indeed, the Hubble diagram of distant SNIa shows that they can yield remarkably precise relative distances; even though they display large variations in brightness, with detailed knowledge of the shape of the light curve and colors, the relative intrinsic brightness of a single SNIa can be predicted to $\Delta m \simeq 0.2$ mag and its distance estimated to $\simeq 10\%$ accuracy [24–26]. Distant SNIa constrain the global deviations from a linear Hubble law including those from cosmic deceleration [27–28].

17.3. Type II supernovae (SNII)

A SNII occurs when a massive star has accumulated 1.4 solar masses of iron group elements in its core; there is then no source of nuclear energy and the core collapses by the Chandrasekhar instability. The collapse to a neutron star releases a large gravitational binding energy, some of which powers an explosion. The large variety of envelopes around collapsing cores means that SNII are not at all uniform in their properties. However, their distances can be calibrated absolutely by the fairly reliable "expanding photosphere method" (EPM). In principle the spectral temperature and absolute flux yield the source angular size; spectral lines yield the expansion velocity, which combined with elapsed time gives a physical size; and the two sizes yield a distance. Models of real photospheres are not so simple but yield individual distances accurate to about 20% [29]. This is in principle an independent absolute distance, but is verified by comparison with Cepheids in several cases, the distant Hubble diagram and Tully-Fisher distance ratios in several others, and by multiple-epoch fits of the same object.

17.4. Planetary nebula luminosity function (PNLF)

A planetary nebula (PN) forms when the gaseous envelope is ejected from a low-mass star as its core collapses to a white dwarf. We see bright fluorescent radiation from the ejected gas shell, excited by UV light from the hot proto-white dwarf. The line radiation makes PN's easy to find and measure even in far-away galaxies; a bright galaxy can have tens of thousands, of which hundreds are bright enough to use to construct a PNLF. It is found empirically that the range of PN brightnesses has a sharp upper cutoff, possibly as a consequence of the very narrow range in core masses that result from normal stellar evolution. The cutoff appears to provide a good empirical standard candle [30], verified by comparison with SBF distance ratios.

17.5. Surface brightness fluctuations (SBF)

In images of galaxies, individual stars are generally too crowded to resolve. However, with modern linear detectors, it is still possible to measure the moments of the distribution of stellar brightness in a population (in particular, the brightness-weighted average stellar brightness) from surface brightness fluctuations. Stellar populations in elliptical galaxies appear to be universal enough for this to be one of the most precise standard candles, as verified by comparison with PNLF and Cepheids, although absolute calibration must be done on the bulge components of spiral galaxies. With HST data it can now be applied into the far Hubble flow [31–32].

17.6. Tully-Fisher (TF) and diameter-dispersion (D_n–σ)

The TF relation refers to a correlation of the properties of whole spiral galaxies, between rotational velocity and total luminosity. In rough terms, the relation can be understood as a relation between mass and luminosity, but given the variation in structural properties and stellar populations the narrow relation is a surprisingly good relative distance indicator. The TF distance ratios and precision have been verified by cross-checking against all of the above methods, and against the Hubble flow, particularly galaxy cluster averages, which permit greater precision. HST has permitted absolute calibration of TF in a larger, more representative, and more distant sample, including galaxies in the Virgo and Fornax clusters [33]. For elliptical galaxies, a similar relation ("D_n–σ") is particularly useful for verifying distance ratios of galaxy clusters, whose cores contain almost no spirals.

17.7. Brightest cluster galaxies (BCG)

As a result of agglomeration, rich clusters of galaxies have accumulated the largest and brightest galaxies in the universe in their centers, which are remarkably homogenous. They provide a check on the approach to uniform Hubble flow on large scales [2–3] and are now tied to an absolute scale via SBF [34].

17.8. Globular cluster luminosity function (GCLF)

Many galaxies have systems of globular clusters orbiting them, each of which contain hundreds of thousands of stars and hence is visible at large distances. Empirically it appears that similar galaxies have similar distributions of globular cluster luminosity [35]

17.9. Sunyaev-Zeldovich effect (SZ)

The electron density and temperature of the hot plasma in a cluster of galaxies can be measured in two ways which depend differently on distance: the thermal x-ray emission, which is mostly bremsstrahlung by hot electrons, and the Sunyaev-Zeldovich effect on the microwave background, caused by Compton scattering off the same electrons. This provides in principle an absolute calibration. Although the model has other unconstrained parameters, such as the gas geometry, which limit the precision and reliability of distances, in the handful of cases which have been studied most recently the distances are broadly in accord with those obtained by the other techniques. [36–38]

17.10. Gravitational lenses (GL)

The time delay δt between different images of a high redshift gravitationally lensed quasar is $\delta t = C\delta\theta^2/H_0 \approx 1$ yr for image separations $\delta\theta$ of the order of arcseconds, with a numerical factor C typically of order unity determined by the specific lens geometry (the angular distribution of the lensing matter) and background cosmology. Variability of the double quasar 0957+561 has permitted measurements of δt from time series correlation, 417 ± 3 days [39–40], with well controlled theoretical errors in deriving constraints on H_0 [41]; measurements of other lens systems are also improving [42]. It is an amazing sanity check that this technique, which relies on no other intermediate steps for its calibration, gives estimates on the scale of the Hubble length which are consistent with local measures of H_0.

Table 17.2: Some recent estimates of Hubble's constant

Technique	Calibration*	Ties to Hubble flow	Result* ($\mathrm{km\ s^{-1}\ Mpc^{-1}}$)	Ref.
EPM	EPM model, Cepheids	Direct EPM Hubble Diagram + Flow model or TF	73 ± 6 ± 7	[29,19]
SNeIa	Host galaxy Cepheids	Direct SNIa Hubble Diagram	63 ± 3.4	[25]
			58 ± 8	[21]
Clusters	Virgo mean (M100 Cepheids)	Virgo infall model	81 ± 11†	[19]
	+ local + M101 Cepheids	Virgo/Coma ratio	73–77 ± 10†	[19]
		Cluster TF + LS flow model fit	82 ± 11†	[19]
	M96 Cepheids	LeoI to Virgo and Coma	69 ± 8	[22]
Field TF	Local Cepheids	Field TF Hubble Diagram + Malmquist bias correction	80 ± 10	[43]
BCG	SBF, Cepheids	BCG	82 ± 8	[34]
SZ	SZ model + X-ray maps + SZ maps	Single cluster velocities A478,A2142,A2256	54 ± 14	[38]
		Coma	74 ± 29	[37]
GL	Lens model, time delay	Direct, Q0957+561	63 ± 12	[40]

* For all methods except SZ and GL, add a common multiplicative error of ±0.15 mag or 7% in H_0 for absolute calibration of Cepheids. These values assume the pre-Hipparcos calibration of the Cepheid PL relation.

† Plus Virgo depth uncertainty (scales with M100/Virgo ratio).

17.11. Estimates of H_0

The central idea is to find "landmark" systems whose distance is given by more than one technique. The number of techniques and the range of each has now increased enough for reliable overlapping calibration at each stage of the distance scale. The reason for the diversity of estimates of the Hubble constant lies in the many different ways to combine these techniques to obtain an absolute distance calibration in the Hubble flow. There is now broad agreement within the errors among a wide variety of semi-independent ladders with different systematics. As examples, we cite a variety of (somewhat arbitrarily chosen) independent methods, which illustrate some of the choices and tradeoffs, summarized in Table 17.2. Note that most of the quoted values depend in common on the absolute Cepheid calibration.

1. Expanding photosphere method (EPM) distances give an absolute calibration to objects in the distant Hubble flow. A small sample of these direct distances with small flow corrections gives $H_0 = 73 \pm 6$ (statistical) $\pm$ 7 (systematic).The distance estimates and limits on the systematic error component are verified by Cepheid distances in three cases, where the Cepheid/EPM distances come out to 1.02 ± 0.08 (LMC), $1.01^{+0.23}_{-0.17}$ (M101) and 1.13 ± 0.28 (M100).
2. With HST, it is now possible to calibrate SNIa directly with Cepheid distances to host galaxies. The light from brighter SNIa decays more slowly than from faint ones, so the best fits to the distant Hubble diagram include information about the light curve shape rather than simply assuming uniformity.
3. The distance to Virgo or any other local cluster is tied to H_0 via the distant Hubble diagram for TF or D_n–σ distances for galaxies in distant clusters. This can be done with a large scale flow model fit to many clusters or using the distance ratio to a fiducial reference such as the Coma cluster.
4. TF comparison with distant field galaxies in the Hubble flow (after corrections for Malmquist bias in the samples, which is worse than in cluster samples) yield $H_0 = 80 \pm 10$ km s^{-1} Mpc^{-1}.
5. The distant BCG sample is now calibrated with SBF directly.
6. Recent SZ and GL estimates lie squarely in the range of the other techniques and are completely independent of them, although errors are not yet well constrained with such small samples.

The central values by most reliably calibrated methods lie in the range $H_0 = 60$ to 80 km s^{-1} Mpc^{-1}, and indeed this corresponds roughly with the range of estimates expected from the internally estimated errors. Thus systematic errors are at least not overwhelming, although there are still discrepencies which are not understood.

Footnote and References:

* This simple Newtonian description is valid to first order in v; the role of the Hubble constant in relativistic world-models is summarized in the Big-Bang Cosmology section (Sec. 15).

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18. DARK MATTER

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There is strong evidence from a variety of different observations for a large amount of dark matter in the universe [1]. The phrase "dark matter" means matter whose existence has been inferred only through its gravitational effects. There is also extensive circumstantial evidence that at least some of this dark matter is nonbaryonic: that is, composed of elementary particles other than protons, neutrons, and electrons. These particles must have survived from the Big Bang, and therefore must either be stable or have lifetimes in excess of the current age of the universe.

The abundance of dark matter is usually quoted in terms of its mass density $\rho_{\rm dm}$ in units of the critical density, $\Omega_{\rm dm} = \rho_{\rm dm}/\rho_{\rm c}$; the critical density $\rho_{\rm c}$ is defined in Eq. (15.5) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The total amount of visible matter (that is, matter whose existence is inferred from its emission or absorption of photons) is roughly $\Omega_{\rm vis} \simeq 0.005$, with an uncertainty of at least a factor of two.

The strongest evidence for dark matter is from the rotation curves of spiral galaxies [1,2]. In these observations, the circular velocity $v_{\rm c}$ of hydrogen clouds surrounding the galaxy is measured (via Doppler shift) as a function of radius r. If there were no dark matter, at large r we would find $v_{\rm c}^2 \simeq G_N M_{\rm vis}/r$, since the visible mass $M_{\rm vis}$ of a spiral galaxy is concentrated at its center. However, observations of many spiral galaxies instead find a velocity $v_{\rm c}$ which is independent of r at large r, with a typical value $v_{\rm c} \sim 200\,{\rm km\ s}^{-1}$. Such a "flat rotation curve" implies that the total mass within radius r grows linearly with r, $M_{\rm tot}(r) \simeq G_N^{-1} v_{\rm c}^2 r$. A self-gravitating ball of ideal gas at a uniform temperature of $kT = \frac{1}{2} m_{\rm dm} v_{\rm c}^2$ would have this mass profile; here $m_{\rm dm}$ is the mass of one dark matter particle. The rotation curves are measured out to some tens of kiloparsecs, implying a total mass within this radius which is typically about ten times the visible mass. This would imply $\Omega_{\rm dm} \gtrsim 10\,\Omega_{\rm vis} \simeq 0.05$. In our own galaxy, estimates of the local density of dark matter typically give $\rho_{\rm dm} \simeq 0.3\,{\rm GeV\ cm}^{-3}$, but this result depends sensitively on how the halo of dark matter is modeled.

Other indications of the presence of dark matter come from observations of the motion of galaxies and hot gas in clusters of galaxies [3]. The overall result is that $\Omega_{\rm dm} \sim 0.2$. Studies of large-scale velocity fields result in $\Omega_{\rm dm} \gtrsim 0.3$ [4]. However, these methods of determining $\Omega_{\rm dm}$ require some astrophysical assumptions about how galaxies form.

None of these observations give us any direct indication of the nature of the dark matter. If it is baryonic, the forms it can take are severely restricted, since most forms of ordinary matter readily emit and absorb photons in at least one observable frequency band [5]. Possible exceptions include remnants (white dwarfs, neutron stars, black holes) of an early generation of massive stars, or smaller objects which never initiated nuclear burning (and would therefore have masses less than about $0.1\,M_\odot$). These massive compact halo objects are collectively called machos. Results from one of the ongoing searches for machos via gravitational lensing effects [6] indicate that a significant fraction (roughly 20% to 60%, depending on the details of the model of the galaxy which is assumed) of the mass of our galaxy's halo is composed of machos.

There are, also, several indirect arguments which argue for a substantial amount of nonbaryonic dark matter. First, nucleosynthesis gives the limits $0.010 \le \Omega_{\rm b} h_0^2 \le 0.016$ for the total mass of baryons; h_0 is defined in Eq. (15.6) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The upper limit on $\Omega_{\rm b}$ is substantially below the value $\Omega_{\rm dm} \gtrsim 0.3$ given by large scale measurements, even if h_0 is near the lower end of its optimistically allowed range, $0.4 \le h_0 \le 1.0$. A second, purely theoretical argument is that inflationary models (widely regarded as providing explanations of a number of otherwise puzzling paradoxes) generically predict $\Omega_{\rm total} = 1$. Finally, it is difficult to construct a model of galaxy formation without nonbaryonic dark matter that predicts sufficiently small fluctuations in the cosmic microwave background radiation [7].

For purposes of galaxy formation models, nonbaryonic dark matter is classified as "hot" or "cold," depending on whether the dark matter particles were relativistic or nonrelativistic at the time when the horizon of the universe enclosed enough matter to form a galaxy. If the dark matter particles are in thermal equilibrium with the baryons and radiation, then only the mass of a dark matter particle is relevant to knowing whether the dark matter is hot or cold, with the dividing line being $m_{\rm dm} \sim 1\,{\rm keV}$. In addition, specifying a model requires giving the power spectrum of initial density fluctuations. Inflationary models generically predict a power spectrum which is nearly scale invariant. Given this, models with only cold dark matter are much more successful than models with only hot dark matter at reproducing the observed structure of our universe, but there are still serious discrepancies [8]. Some of the suggestions proposed to alleviate these include a nonzero value of the cosmological constant Λ [9], significant deviations from scale invariance in the spectrum of initial fluctuations [10], and a mixture of both hot and cold dark matter [11]. Another class of models uses mass fluctuations due to topological defects [12].

The best candidate for hot dark matter is one of the three neutrinos, endowed with a Majorana mass m_ν. Such a neutrino would contribute $\Omega_\nu = 0.56\,G_N T_0^3 H_0^{-2} m_\nu = m_\nu/(92\,h_0^2\,{\rm eV})$, where T_0 is the present temperature of the cosmic microwave background radiation. There is another constraint on neutrinos (or any light fermions) if they are to comprise the halos of dwarf galaxies: the Fermi–Dirac distribution in phase space restricts the number of neutrinos that can be put into a halo [13], and this implies a lower limit on the neutrino mass of $m_\nu \gtrsim 80\,{\rm eV}$.

There are no presently known particles which could be cold dark matter. However, many proposed extensions of the Standard Model predict a stable (or sufficiently long-lived) particle. The key question then becomes the predicted value of $\Omega_{\rm dm}$.

If the particle is its own antiparticle (or there are particles and antiparticles present in equal numbers), and these particles were in thermal equilibrium with radiation at least until they became nonrelativistic, then their relic abundance is determined by their annihilation cross section $\sigma_{\rm ann}$: $\Omega_{\rm dm} \sim G_N^{3/2} T_0^3 H_0^{-2} \langle\sigma_{\rm ann} v_{\rm rel}\rangle^{-1}$. Here $v_{\rm rel}$ is the relative velocity of the two incoming dark matter particles, and the angle brackets denote an averaging over a thermal distribution of velocities for each at the freezeout temperature $T_{\rm fr}$ when the dark matter particles go out of thermal equilibrium with radiation; typically $T_{\rm fr} \simeq \frac{1}{20} m_{\rm dm}$. One then finds (putting in appropriate numerical factors) that $\Omega_{\rm dm} h_0^2 \simeq 3 \times 10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}/\langle\sigma_{\rm ann} v_{\rm rel}\rangle$. The value of $\langle\sigma_{\rm ann} v_{\rm rel}\rangle$ needed for $\Omega_{\rm dm} \simeq 1$ is remarkably close to what one would expect for a weakly interacting massive particle (wimp) with a mass of $m_{\rm dm} = 100\,{\rm GeV}$: $\langle\sigma_{\rm ann} v_{\rm rel}\rangle \sim \alpha^2/8\pi m_{\rm dm}^2 \sim 3 \times 10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}$.

If the dark matter particle is not its own antiparticle, and the number of particles minus antiparticles is conserved, then an initial asymmetry in the abundances of particles and antiparticles will be preserved, and can give relic abundances much larger than those predicted above.

If the dark matter particles were never in thermal equilibrium with radiation, then their abundance today must be calculated in some other way, and will in general depend on the precise initial conditions which are assumed.

The two best known and most studied cold dark matter candidates are the neutralino and the axion. The neutralino is predicted by supersymmetric extensions of the Standard Model [14,15]. It qualifies as a wimp, with a theoretically expected mass in the range of tens to hundreds of GeV. The axion is predicted by extensions of the Standard Model which resolve the strong CP problem [16]. Its mass must be approximately $10^{-5}\,{\rm eV}$ if it is to be a significant component of the dark matter. Axions can occur in the early universe form of a Bose condensate which never comes into thermal equilibrium. The axions in this condensate are always nonrelativistic, and can be a significant component of the dark matter if the axion mass is approximately $10^{-5}\,{\rm eV}$.

There are prospects for direct experimental detection of both these candidates (and other wimp candidates as well). Wimps will scatter off nuclei at a calculable rate, and produce observable nuclear recoils [15,17]. This technique has been used to show that all the dark matter cannot consist of massive Dirac neutrinos or scalar neutrinos (predicted by supersymmetric models) with masses in the range of $10\,\mathrm{GeV} \lesssim m_{\mathrm{dm}} \lesssim 4\,\mathrm{TeV}$ [18]. The neutralino is harder to detect because its scattering cross section with nuclei is considerably smaller. Condensed axions can be detected by axion to photon conversion in an inhomogeneous magnetic field, and limits on the allowed axion-photon coupling (for certain ranges of the axion mass) have been set [16]. Both types of detection experiments are continuing.

Wimp candidates can have indirect signatures as well, via present-day annihilations into particles which can be detected as cosmic rays [15]. The most promising possibility arises from the fact that wimps collect at the centers of the sun and the earth, thus greatly increasing their annihilation rate, and producing high energy neutrinos which can escape and arrive at the earth's surface in potentially observable numbers.

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19. COSMIC BACKGROUND RADIATION

Revised April 1998 by G.F. Smoot (LBNL) and D. Scott (University of British Columbia).

19.1. Introduction

The observed cosmic microwave background (CMB) radiation provides strong evidence for the hot big bang. The success of primordial nucleosynthesis calculations (see Sec. 16, "Big-bang nucleosynthesis") requires a cosmic background radiation (CBR) characterized by a temperature $kT \sim 1\,\mathrm{MeV}$ at a redshift of $z \simeq 10^9$. In their pioneering work, Gamow, Alpher, and Herman [1] realized this and predicted the existence of a faint residual relic, primordial radiation, with a present temperature of a few degrees. The observed CMB is interpreted as the current manifestation of the required CBR.

The CMB was serendipitously discovered by Penzias and Wilson [2] in 1965. Its spectrum is well characterized by a $2.73 \pm 0.01\,\mathrm{K}$ black-body (Planckian) spectrum over more than three decades in frequency (see Fig. 19.1). A non-interacting Planckian distribution of temperature T_i at redshift z_i transforms with the universal expansion to another Planckian distribution at redshift z_r with temperature $T_r/(1+z_r) = T_i/(1+z_i)$. Hence thermal equilibrium, once established (e.g. at the nucleosynthesis epoch), is preserved by the expansion, in spite of the fact that photons decoupled from matter at early times. Because there are about 10^9 photons per nucleon, the transition from the ionized primordial plasma to neutral atoms at $z \sim 1000$ does not significantly alter the CBR spectrum [3].

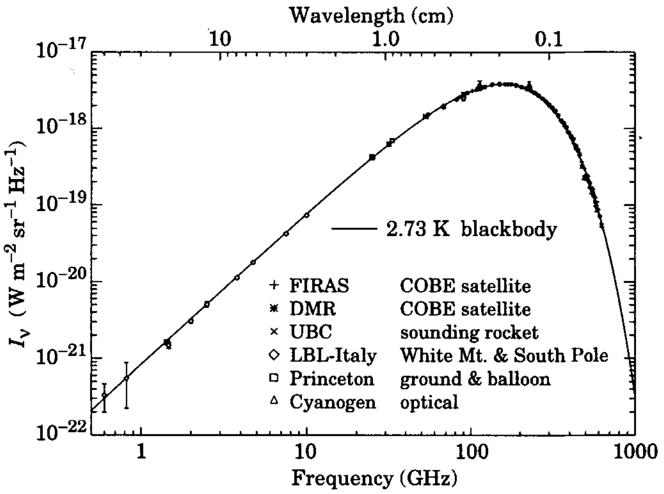

Figure 19.1: Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at 10 cm and longer wavelengths. (References for this figure are at the end of this section under "CMB Spectrum References.")

19.2. The CMB frequency spectrum

The remarkable precision with which the CMB spectrum is fitted by a Planckian distribution provides limits on possible energy releases in the early Universe, at roughly the fractional level of 10^{-4} of the CBR energy, for redshifts $\lesssim 10^7$ (corresponding to epochs $\gtrsim 1$ year). The following three important classes of theoretical spectral distortions (see Fig. 19.2) generally correspond to energy releases at different epochs. The distortion results from the CBR photon interactions with a hot electron gas at temperature T_e.

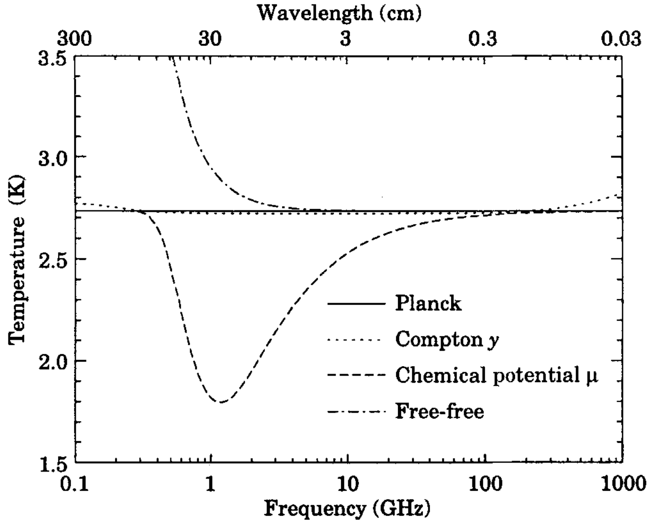

Figure 19.2: The shapes of expected, but so far unobserved, CMB distortions, resulting from energy-releasing processes at different epochs.

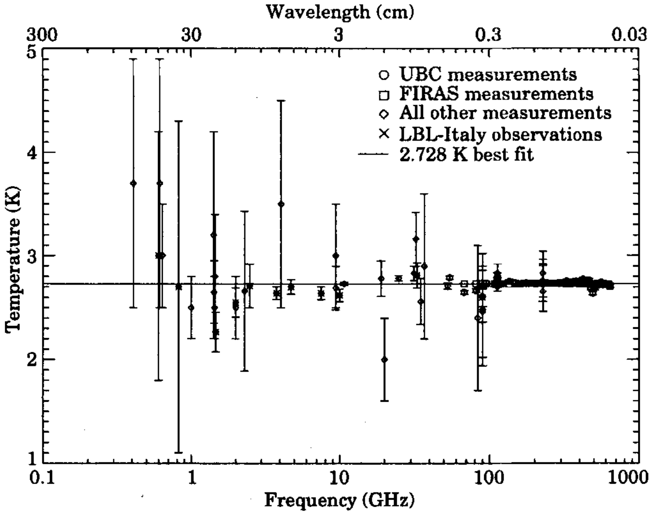

Figure 19.3: Observed thermodynamic temperature as a function frequency.

19.2.1. ***Compton distortion*:** Late energy release ($z \lesssim 10^5$). Compton scattering ($\gamma e \to \gamma' e'$) of the CBR photons by a hot electron gas creates spectral distortions by transfering energy from the electrons to the photons. Compton scattering cannot achieve thermal equilibrium for $y < 1$, where

$$y = \int_0^z \frac{kT_e(z') - kT_\gamma(z')}{m_e c^2}\, \sigma_T\, n_e(z')\, c\, \frac{dt}{dz'}\, dz' \,, \tag{19.1}$$

is the integral of the number of interactions, $\sigma_T\, n_e(z)\, c\, dt$, times the mean-fractional photon-energy change per collision [4]. For $T_e \gg T_\gamma$ y is also proportional to the integral of the electron pressure $n_e kT_e$ along the line of sight. For standard thermal histories $y < 1$ for epochs later than $z \simeq 10^5$.

The resulting CMB distortion is a temperature decrement

$$\Delta T_{\mathrm{RJ}} = -2y\, T_\gamma \tag{19.2}$$

in the Rayleigh-Jeans ($h\nu/kT \ll 1$) portion of the spectrum, and a rapid rise in temperature in the Wien ($h\nu/kT \gg 1$) region, *i.e.* photons are shifted from low to high frequencies. The magnitude of the distortion is related to the total energy transfer [4] ΔE by

$$\Delta E/E_{\mathrm{CBR}} = e^{4y} - 1 \simeq 4y \,. \tag{19.3}$$

A prime candidate for producing a Comptonized spectrum is a hot intergalactic medium. A hot ($T_e > 10^5\,\mathrm{K}$) medium in clusters of galaxies can and does produce a partially Comptonized spectrum as seen through the cluster, known as the Sunyaev-Zel'dovich effect. Based upon X-ray data, the predicted large angular scale total combined effect of the hot intracluster medium should produce $y \lesssim 10^{-6}$ [5].

19.2.2. ***Bose-Einstein or chemical potential distortion***: Early energy release ($z \sim 10^5$–10^7). After many Compton scatterings ($y > 1$), the photons and electrons will reach statistical (not thermodynamic) equilibrium, because Compton scattering conserves photon number. This equilibrium is described by the Bose-Einstein distribution with non-zero chemical potential:

$$n = \frac{1}{e^{x+\mu_0} - 1}\,, \tag{19.4}$$

where $x \equiv h\nu/kT$ and $\mu_0 \simeq 1.4\ \Delta E/E_{\mathrm{CBR}}$, with μ_0 being the dimensionless chemical potential that is required.

The collisions of electrons with nuclei in the plasma produce free-free (thermal bremsstrahlung) radiation: $eZ \to eZ\gamma$. Free-free emission thermalizes the spectrum to the plasma temperature at long wavelengths. Including this effect, the chemical potential becomes frequency-dependent,

$$\mu(x) = \mu_0 e^{-2x_b/x}\,, \tag{19.5}$$

where x_b is the transition frequency at which Compton scattering of photons to higher frequencies is balanced by free-free creation of new photons. The resulting spectrum has a sharp drop in brightness temperature at centimeter wavelengths [6]. The minimum wavelength is determined by Ω_B.

The equilibrium Bose-Einstein distribution results from the oldest non-equilibrium processes ($10^5 < z < 10^7$), such as the decay of relic particles or primordial inhomogeneities. Note that free-free emission (thermal bremsstrahlung) and radiative-Compton scattering effectively erase any distortions [7] to a Planckian spectrum for epochs earlier than $z \sim 10^7$.

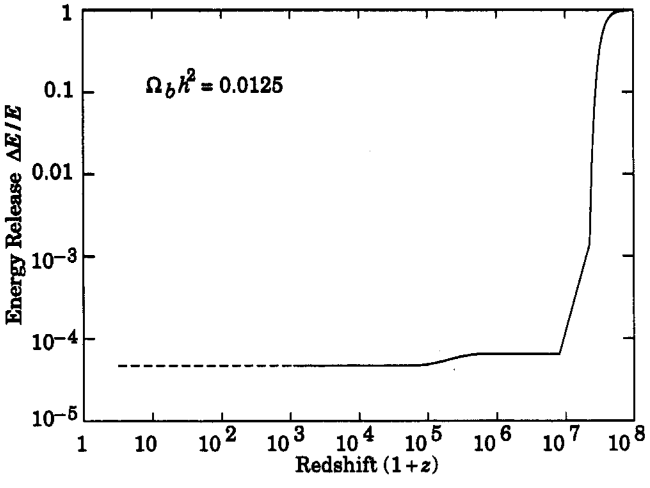

Figure 19.4: Upper Limits (95% CL) on fractional energy ($\Delta E/E_{\mathrm{CBR}}$) releases from processes at different epochs as set by resulting lack of CMB spectral distortions. These can be translated into constraints on the mass, lifetime and photon branching ratio of unstable relic particles, with some additional dependence on cosmological parameters such as Ω_B [9,10].

19.2.3. ***Free-free distortion***: Very late energy release ($z \ll 10^3$). Free-free emission can create rather than erase spectral distortion in the late Universe, for recent reionization ($z < 10^3$) and from a warm intergalactic medium. The distortion arises because of the lack of Comptonization at recent epochs. The effect on the present-day CMB spectrum is described by

$$\Delta T_{ff} = T_\gamma\, Y_{ff}/x^2\,, \tag{19.6}$$

where T_γ is the undistorted photon temperature, x is the dimensionless frequency, and Y_{ff}/x^2 is the optical depth to free-free emission:

$$Y_{ff} = \int_0^z \frac{T_e(z') - T_\gamma(z')}{T_e(z')}\, \frac{8\pi e^6 h^2 n_e^2\, g}{3m_e(kT_\gamma)^3\, \sqrt{6\pi\, m_e\, kT_e}}\, \frac{dt}{dz'} dz'\,. \tag{19.7}$$

Here h is Planck's constant, n_e is the electron density and g is the Gaunt factor [8].

19.2.4. ***Spectrum summary***: The CMB spectrum is consistent with a blackbody spectrum over more than three decades of frequency around the peak. A least-squares fit to all CMB measurements yields:

$$\begin{aligned}
&T_\gamma = 2.728 \pm 0.002\ \mathrm{K} \quad (1\sigma\ \text{error})\\
&n_\gamma = (2\zeta(3)/\pi^2)T_\gamma^3 \simeq 412\,\mathrm{cm}^{-3}\\
&\rho_\gamma = (\pi^2/15)T_\gamma^4 \simeq 4.68 \times 10^{-34}\,\mathrm{g\,cm}^{-3} \simeq 0.262\,\mathrm{eV\,cm}^{-3}\\
&|y| < 1.2 \times 10^{-5} \qquad (95\%\ \mathrm{CL})\\
&|\mu_0| < 9 \times 10^{-5} \qquad (95\%\ \mathrm{CL})\\
&|Y_{ff}| < 1.9 \times 10^{-5} \quad (95\%\ \mathrm{CL})
\end{aligned}$$

The limits here [11] correspond to limits [11–13] on energetic processes $\Delta E/E_{\mathrm{CBR}} < 2 \times 10^{-4}$ occurring between redshifts 10^3 and 5×10^6 (see Fig. 19.4). The best-fit temperature from the COBE FIRAS experiment is $T_\gamma = 2.728 \pm 0.002\,\mathrm{K}$ [11].

19.3. Deviations from isotropy

Penzias and Wilson reported that the CMB was isotropic and unpolarized to the 10% level. Current observations show that the CMB is unpolarized at the 10^{-5} level but has a dipole anisotropy at the 10^{-3} level, with smaller-scale anisotropies at the 10^{-5} level. Standard theories predict anisotropies in linear polarization well below currently achievable levels, but temperature anisotropies of roughly the amplitude now being detected.

It is customary to express the CMB temperature anisotropies on the sky in a spherical harmonic expansion,

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)\,, \tag{19.8}$$

and to discuss the various multipole amplitudes. The power at a given angular scale is roughly $\ell \sum_m |a_{\ell m}|^2/4\pi$, with $\ell \sim 1/\theta$.

19.3.1. ***The dipole***: The largest anisotropy is in the $\ell = 1$ (dipole) first spherical harmonic, with amplitude at the level of $\Delta T/T = 1.23 \times 10^{-3}$. The dipole is interpreted as the result of the Doppler shift caused by the solar system motion relative to the nearly isotropic blackbody field. The motion of the observer (receiver) with velocity $\beta = v/c$ relative to an isotropic Planckian radiation field of temperature T_0 produces a Doppler-shifted temperature

$$\begin{aligned}
T(\theta) &= T_0(1-\beta^2)^{1/2}/(1-\beta\cos\theta)\\
&= T_0\left(1 + \beta\cos\theta + (\beta^2/2)\cos 2\theta + O(\beta^3)\right)\,.
\end{aligned} \tag{19.9}$$

The implied velocity [11,14] for the solar-system barycenter is $\beta = 0.001236 \pm 0.000002$ (68% CL) or $v = 371 \pm 0.5\,\mathrm{km\,s}^{-1}$, assuming a value $T_0 = 2.728 \pm 0.002\,\mathrm{K}$, towards $(\alpha,\delta) = (11.20^{\mathrm{h}} \pm 0.01^{\mathrm{h}}, -7.22^\circ \pm 0.08^\circ)$, or $(\ell, b) = (264.31^\circ \pm 0.17^\circ, 48.05^\circ \pm 0.10^\circ)$. Such a solar-system velocity implies a velocity for the Galaxy and the Local Group of galaxies relative to the CMB. The derived velocity is $v_{\mathrm{LG}} = 627 \pm 22\,\mathrm{km\,s}^{-1}$

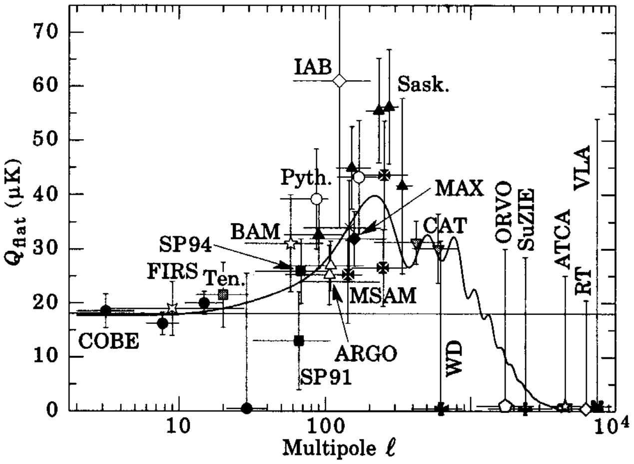

Figure 19.5: Current status of CMB anisotropy observations, adapted from Scott, Silk, & White (1995) [18]. This is a representation of the results from COBE, together with a wide range of ground- and balloon-based experiments which have operated in the last few years. Plotted are the quadrupole amplitudes for a flat (unprocessed scale-invariant spectrum of primordial perturbations, *i.e.*, a horizontal line) anisotropy spectrum that would give the observed results for each experiment. In other words each point is the normalization of a flat spectrum derived from the individual experiments. The vertical error bars represent estimates of 68% CL, while the upper limits are at 95% CL. Horizontal bars indicate the range of ℓ values sampled. The curve indicates the expected spectrum for a standard CDM model ($\Omega_0 = 1, \Omega_B = 0.05, h = 0.5$), although true comparison with models should involve convolution of this curve with each experimental filter function. The dashed line is the best fitted flat spectrum derived from the COBE data alone [24]. (References for this figure are at the end of this section under "CMB Anisotropy References.")

toward $(\ell, b) = (276° \pm 3°, 30° \pm 3°)$, where most of the error comes from uncertainty in the velocity of the solar system relative to the Local Group.

The Doppler effect of this velocity and of the velocity of the Earth around the Sun, as well as any velocity of the receiver relative to the Earth, is normally removed for the purposes of CMB anisotropy study. The resulting high degree of CMB isotropy is the strongest evidence for the validity of the Robertson-Walker metric.

19.3.2. ***The quadrupole***: The rms quadrupole anisotropy amplitude is defined through $Q^2_{\rm rms}/T^2_\gamma = \sum_m |a_{2m}|^2 / 4\pi$. The current estimate of its value is $4\,\mu{\rm K} \leq Q_{\rm rms} \leq 28\,\mu{\rm K}$ for a 95% confidence interval [15]. The uncertainty here includes both statistical errors and systematic errors, which are dominated by the effects of galactic emission modelling. This level of quadrupole anisotropy allows one to set general limits on anisotropic expansion, shear, and vorticity; all such dimensionless quantities are constrained to be less than about 10^{-5}.

For specific homogeneous cosmologies, fits to the whole anisotropy pattern allow stringent limits to be placed on, for example, the global rotation at the level of about 10^{-7} of the expansion rate [16].

19.3.3. ***Smaller angular scales***: The COBE-discovered [17] higher-order ($\ell > 2$) anisotropy is interpreted as being the result of perturbations in the energy density of the early Universe, manifesting themselves at the epoch of the CMB's last scattering. Hence the detection of these anisotropies has provided evidence for the existence of primordial density perturbations which grew through gravitational instability to form all the structure we observe today.

In the standard scenario the last scattering takes place at a redshift of approximately 1100, at which epoch the large number of photons was no longer able to keep the hydrogen sufficiently ionized. The optical thickness of the cosmic photosphere is roughly $\Delta z \sim 100$ or about 5 arcminutes, so that features smaller than this size are damped.

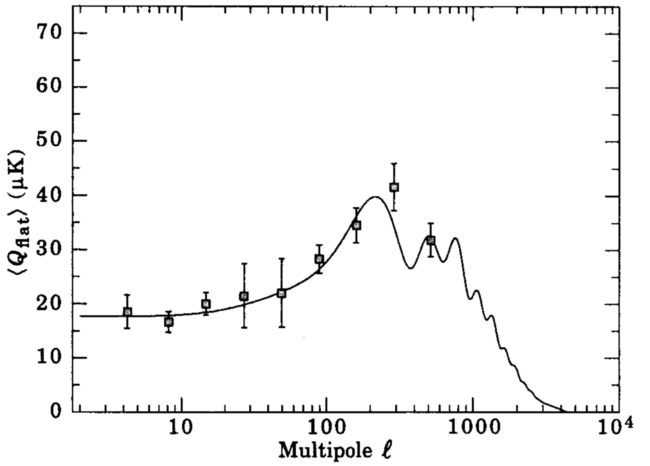

Figure 19.6: This is a binned version of the previous figure. To obtain this figure we took all reported detections, split the multipole range into equal logarithmic 'bins,' and calculated the weighted average in each bin. Although this is not a statistically rigorous procedure, the resulting figure gives a visual indication of the current consensus. It is also worth mentioning that there is no strong indication for excess scatter (above Gaussian) within each bin.

Anisotropies are observed on angular scales larger than this damping scale (see Fig. 19.5 and 19.6), and are consistent with those expected from an initially scale-invariant power spectrum (flat = independent of scale) of potential and thus metric fluctuations. It is believed that the large scale structure in the Universe developed through the process of gravitational instability, where small primordial perturbations in energy density were amplified by gravity over the course of time. The initial spectrum of density perturbations can evolve significantly in the epoch $z > 1100$ for causally connected regions (angles $\lesssim 1°\ \Omega^{1/2}_{\rm tot}$). The primary mode of evolution is through adiabatic (acoustic) oscillations, leading to a series of peaks that encode information about the perturbations and geometry of the Universe, as well as information on Ω_0, Ω_B, Ω_Λ (cosmological constant), and H_0 [18]. The location of the first acoustic peak is predicted to be at $\ell \sim 220\,\Omega^{-1/2}_{\rm tot}$ or $\theta \sim 0.3°\ \Omega^{1/2}_{\rm tot}$ and its amplitude is a calculable function of the parameters.

Theoretical models generally predict a power spectrum in spherical harmonic amplitudes, since the models lead to primordial fluctuations and thus $a_{\ell m}$ that are Gaussian random fields, and hence the power spectrum in ℓ is sufficient to characterize the results. The power at each ℓ is $(2\ell+1)C_\ell/(4\pi)$, where $C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$ and a statistically isotropic sky means that all m's are equivalent. For an idealized full-sky observation, the variance of each measured C_ℓ is $[2/(2\ell+1)]C^2_\ell$. This sampling variance (known as cosmic variance) comes about because each C_ℓ is chi-squared distributed with $(2\ell+1)$ degrees of freedom for our observable volume of the Universe [19].

Thomson scattering of the anisotropic radiation field also generates linear polarization at the roughly 5% level [20]. Although difficult to detect, the polarization signal should act as a strong confirmation of the general paradigm.

Figure 19.7 shows the theoretically predicted anisotropy power spectrum for a sample of models, plotted as $\ell(\ell+1)C_\ell$ versus ℓ which is the power per logarithmic interval in ℓ or, equivalently, the two-dimensional power spectrum. If the initial power spectrum of perturbations is the result of quantum mechanical fluctuations produced and amplified during inflation, then the shape of the anisotropy spectrum is coupled to the ratio of contributions from density (scalar) and gravitational wave (tensor) perturbations [21]. If the energy scale of inflation at the appropriate epoch is at the level of $\simeq 10^{16}$GeV, then detection of the effect of gravitons is possible, as well as partial reconstruction of the inflaton potential. If the energy scale is $\lesssim 10^{14}$GeV, then density fluctuations dominate and less constraint is possible.

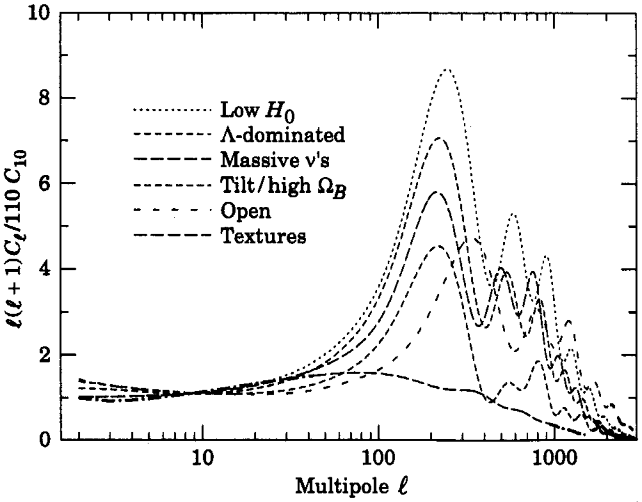

Figure 19.7: Examples of theoretically predicted $\ell(\ell+1)C_\ell$ or CMB anisotropy power spectra [22]. The plot indicates that precise measurements of the CMB anisotropy power spectrum could distinguish between models which are currently favored from galaxy clustering and other considerations. The textures model is from Ref. 23.

Fits to data over smaller angular scales are often quoted as the expected value of the quadrupole $\langle Q\rangle$ for some specific theory, *e.g.* a model with power-law initial conditions (primordial density perturbation power spectrum $P(k) \propto k^n$). The full 4-year COBE DMR data give $\langle Q\rangle = 15.3^{+3.7}_{-2.8}\,\mu$K, after projecting out the slope dependence, while the best-fit slope is $n = 1.2 \pm 0.3$, and for a pure $n = 1$ (scale-invariant potential perturbation) spectrum $\langle Q\rangle\,(n=1) = 18 \pm 1.6\,\mu$K [15,24]. The conventional notation is such that $\langle Q\rangle^2/T_\gamma^2 = 5C_2/4\pi$, and an alternative convention is to plot the "band-power" $\sqrt{\ell(2\ell+1)C_\ell/4\pi}$. The fluctuations measured by other experiments can also be quoted in terms of $Q_{\rm flat}$, the equivalent value of the quadrupole for a flat ($n = 1$) spectrum, as presented in Fig. 19.5.

It now seems clear that there is more power at sub-degree scales than at COBE scales, which provides some model-dependent information on cosmological parameters [18,25], for example Ω_B. In terms of such parameters, fits to the COBE data alone yield $\Omega_0 > 0.34$ at 95% CL [26] and $\Omega_{\rm tot} < 1.5$ also at 95% CL [27], for inflationary models. Only somewhat weak conclusions can be drawn based on the current smaller angular scale data (see Fig. 19.5). A sample preliminary fit [28] finds $\Omega_0\,h^{1/2} \simeq 0.55 \pm 0.10$ ($\equiv$ 68% CL).

However, new data are being acquired at an increasing rate, with a large number of improved ground- and balloon-based experiments being developed. It appears that we are not far from being able to distinguish crudely between currently favored models, and to begin a more precise determination of cosmological parameters. A vigorous suborbital and interferometric program could map out the CMB anisotropy power spectrum to about 10% accuracy and determine several parameters at the 10 to 20% level in the next few years.

There are also now two approved satellite missions: the NASA Millimetre Anisotropy Probe (MAP), scheduled for launch in 2000; and the ESA Planck Surveyor, expected to launch around 2004. The improved sensitivity, freedom from earth-based systematics, and all-sky coverage allow a simultaneous determination of many of the cosmological parameters to unprecedented precision: for example, Ω_0 and n to about 1%; Ω_B and H_0 at the level of a few percent [29].

Furthermore, detailed measurement of the polarization signal provides more precise information on the physical parameters. In particular it allows a clear distinction of any gravity wave contribution, which is crucial to probing the $\sim 10^{16}$ GeV energy range. The fulfillment of this promise may await an even more sensitive generation of satellites.

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20. COSMIC RAYS

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20.1. Primary spectra

The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer. Technically, "primary" cosmic rays are those particles accelerated at astrophysical sources and "secondaries" are those particles produced in interaction of the primaries with interstellar gas. Thus electrons, protons and helium, as well as carbon, oxygen, iron, and other nuclei synthesized in stars, are primaries. Nuclei such as lithium, beryllium, and boron (which are not abundant end-products of stellar nucleosynthesis) are secondaries. Antiprotons and positrons are partly, if not entirely, secondaries, but the fraction of these particles that may be primary is a question of current interest.

Apart from particles associated with solar flares, the cosmic radiation comes from outside the solar system. The incoming charged particles are "modulated" by the solar wind, the expanding magnetized plasma generated by the Sun, which decelerates and partially excludes the lower energy galactic cosmic rays from the inner solar system. There is a significant anticorrelation between solar activity (which has an eleven-year cycle) and the intensity of the cosmic rays with energies below about 10 GeV. In addition, the lower-energy cosmic rays are affected by the geomagnetic field, which they must penetrate to reach the top of the atmosphere. Thus the intensity of any component of the cosmic radiation in the GeV range depends both on the location and time.

There are four different ways to describe the spectra of the components of the cosmic radiation: (1) By particles per unit rigidity. Propagation (and probably also acceleration) through cosmic magnetic fields depends on gyroradius or ***magnetic rigidity***, R, which is gyroradius multiplied by the magnetic field strength:

$$R = \frac{pc}{Ze} = r_L B \, . \tag{20.1}$$

(2) By particles per energy-per-nucleon. Fragmentation of nuclei propagating through the interstellar gas depends on energy per nucleon, since that quantity is approximately conserved when a nucleus breaks up on interaction with the gas. (3) By nucleons per energy-per-nucleon. Production of secondary cosmic rays in the atmosphere depends on the intensity of nucleons per energy-per-nucleon, approximately independently of whether the incident nucleons are free protons or bound in nuclei. (4) By particles per energy-per-nucleus. Air shower experiments that use the atmosphere as a calorimeter generally measure a quantity that is related to total energy per particle.

The units of differential intensity I are $[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathcal{E}^{-1}]$, where $\mathcal{E}$ represents the units of one of the four variables listed above.

The intensity of primary nucleons in the energy range from several GeV to somewhat beyond 100 TeV is given approximately by

$$I_N(E) \approx 1.8\, E^{-\alpha}\, \frac{\text{nucleons}}{\text{cm}^2\ \text{s sr GeV}}\ , \tag{20.2}$$

where E is the energy-per-nucleon (including rest mass energy) and α $(\equiv \gamma + 1) = 2.7$ is the differential spectral index of the cosmic ray flux and γ is the integral spectral index. About 79% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei. The fractions of the primary nuclei are nearly constant over this energy range (possibly with small but interesting variations). Fractions of both primary and secondary incident nuclei are listed in Table 20.1. Figure 20.1 [1] shows the major components as a function of energy at a particular epoch of the solar cycle.

The spectrum of electrons and positrons incident at the top of the atmosphere is steeper than the spectra of protons and nuclei, as shown in Fig. 20.2 [2]. The positron fraction is about 10% in the region in which it is measured (< 20 GeV), but it is not yet fully understood [5].

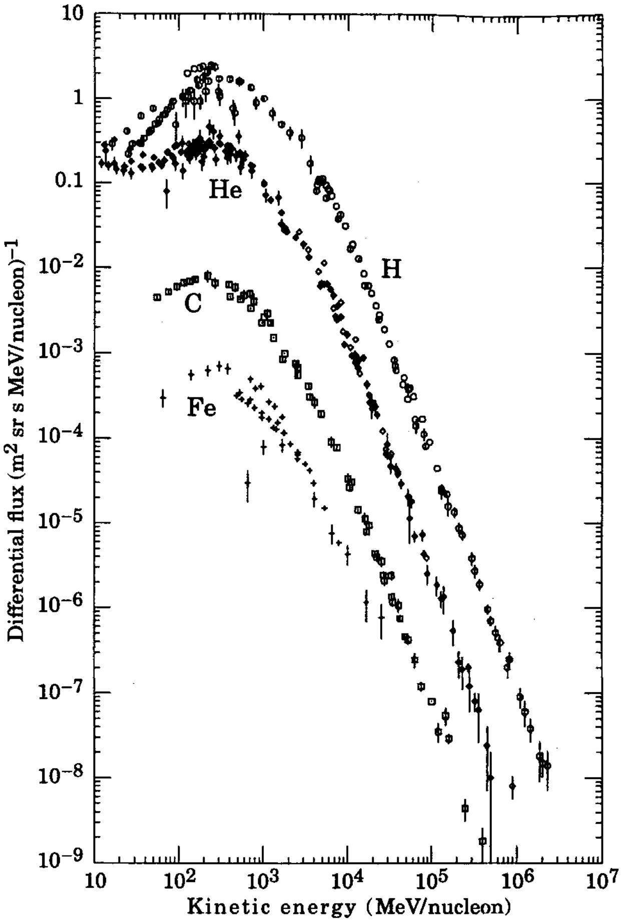

Figure 20.1: Major components of the primary cosmic radiation (from Ref. 1).

Table 20.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [3]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.26×10^{-6} cm^{-2} s^{-1} sr^{-1} (GeV/nucleon)$^{-1}$. Abundances of hydrogen and helium are from Ref. 4.

Z	Element	F	Z	Element	F
1	H	730	13–14	Al-Si	0.19
2	He	34	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

Above 10 GeV the fraction of antiprotons to protons is about 10^{-4}, and there is evidence for the kinematic suppression at lower energy expected for secondary antiprotons [5]. There is at this time no evidence for a significant primary component of antiprotons.

20.2. Cosmic rays in the atmosphere

Figure 20.3 shows the vertical fluxes of the major cosmic ray components in the atmosphere in the energy region where the particles are most numerous (except for electrons, which are most numerous near their critical energy, which is about 81 MeV in air). Except for protons and electrons near the top of the atmosphere, all particles are produced in interactions of the primary cosmic rays in the air. Muons

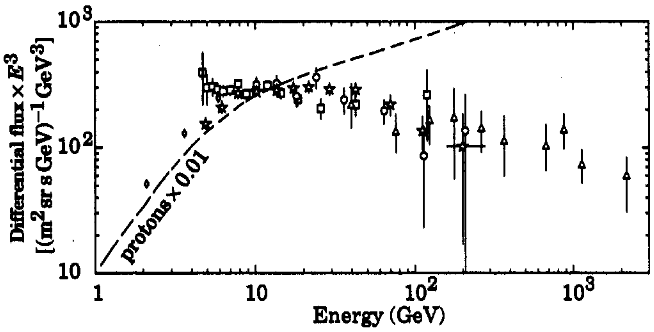

Figure 20.2: Differential spectrum of electrons plus positrons multiplied by E^3 (from Ref. 2).

and neutrinos are products of the decay of charged mesons, while electrons and photons originate in decays of neutral mesons.

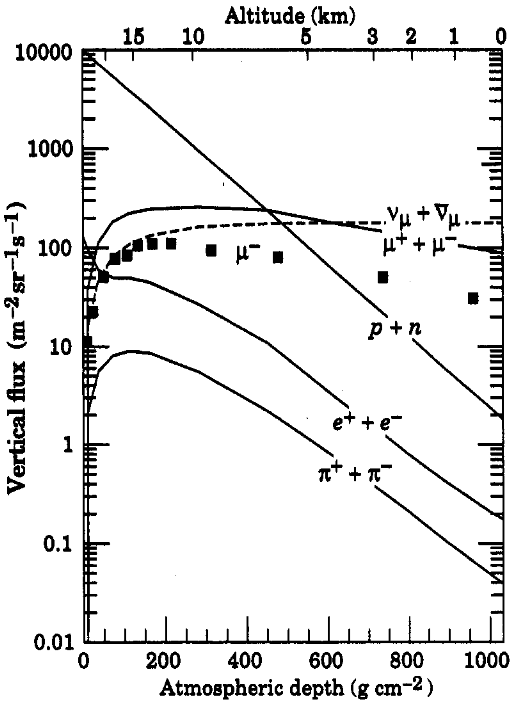

Figure 20.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (20.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [7].

Most measurements are made at ground level or near the top of the atmosphere, but there are also measurements of muons and electrons from airplanes and balloons. Fig. 20.3 includes a recent measurement of negative muons [7]. Since $\mu^+(\mu^-)$ are produced in association with $\nu_\mu(\bar{\nu}_\mu)$, the measurement of muons near the maximum of the intensity curve for the parent pions serves to calibrate the atmospheric ν_μ beam [6]. Because muons typically lose almost two GeV in passing through the atmosphere, the comparison near the production altitude is important for the sub-GeV range of $\nu_\mu(\bar{\nu}_\mu)$ energies.

The flux of cosmic rays through the atmosphere is described by a set of coupled cascade equations with boundary conditions at the top of the atmosphere to match the primary spectrum. Numerical or Monte Carlo calculations are needed to account accurately for decay and energy-loss processes, and for the energy-dependences of the cross sections and of the primary spectral index γ. Approximate analytic solutions are, however, useful in limited regions of energy [8]. For example, the vertical intensity of nucleons at depth X (g cm^{-2}) in the atmosphere is given by

$$I_N(E,X) \approx I_N(E,0)\, e^{-X/\Lambda} , \tag{20.3}$$

where Λ is the attenuation length of nucleons in air.

The corresponding expression for the vertical intensity of charged pions with energy $E_\pi \ll \epsilon_\pi = 115$ GeV is

$$I_\pi(E_\pi,X) \approx \frac{Z_{N\pi}}{\lambda_N} I_N(E_\pi,0)\, e^{-X/\Lambda}\, \frac{X\,E_\pi}{\epsilon_\pi} . \tag{20.4}$$

This expression has a maximum at $t = \Lambda \approx 120$ g cm^{-2}, which corresponds to an altitude of 15 kilometers. The quantity $Z_{N\pi}$ is the spectrum-weighted moment of the inclusive distribution of charged pions in interactions of nucleons with nuclei of the atmosphere. The intensity of low-energy pions is much less than that of nucleons because $Z_{N\pi} \approx 0.079$ is small and because most pions with energy much less than the critical energy ϵ_π decay rather than interact.

20.3. Cosmic rays at the surface

20.3.1. ***Muons***: Muons are the most numerous charged particles at sea level (see Fig. 20.3). Most muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground. Their energy and angular distribution reflect a convolution of production spectrum, energy loss in the atmosphere, and decay. For example, $E_\mu = 2.4$ GeV muons have a decay length of 15 km, which is reduced to 8.7 km by energy loss. The mean energy of muons at the ground is ≈ 4 GeV. The energy spectrum is almost flat below 1 GeV, steepens gradually to reflect the primary spectrum in the 10–100 GeV range, and steepens further at higher energies because pions with $E_\pi > \epsilon_\pi \approx 115$ GeV tend to interact in the atmosphere before they decay. Asymptotically ($E_\mu \gg 1$ TeV), the energy spectrum of atmospheric muons is one power steeper than the primary spectrum. The integral intensity of vertical muons above 1 GeV/c at sea level is ≈ 70 m^{-2}s^{-1}sr^{-1} [9,10]. Experimentalists are familiar with this number in the form $I \approx 1$ cm^{-2} min^{-1} for horizontal detectors.

The overall angular distribution of muons at the ground is $\propto \cos^2\theta$, which is characteristic of muons with $E_\mu \sim 3$ GeV. At lower energy the angular distribution becomes increasingly steeper, while at higher energy it flattens and approaches a $\sec\theta$ distribution for $E_\mu \gg \epsilon_\pi$ and $\theta < 70°$.

Figure 20.4 shows the muon energy spectrum at sea level for two angles. At large angles low energy muons decay before reaching the surface and high energy pions decay before they interact, thus the average muon energy increases. An approximate extrapolation formula valid when muon decay is negligible ($E_\mu > 100/\cos\theta$ GeV) and the curvature of the Earth can be neglected ($\theta < 70°$) is

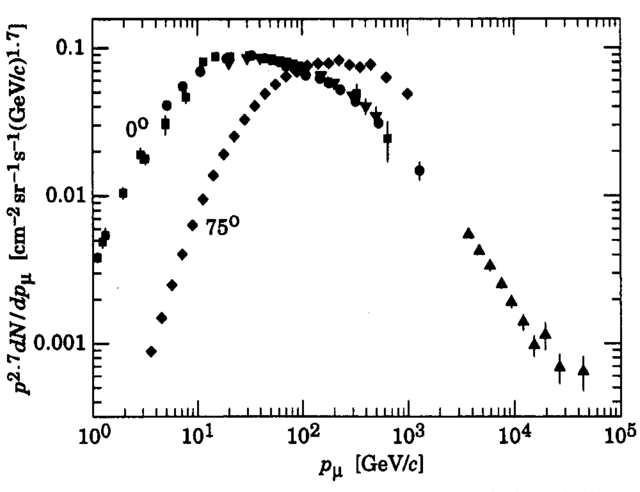

Figure 20.4: Spectrum of muons at $\theta = 0°$ (■ [12], ● [13], ▼ [14], ▲ [15]), and $\theta = 75°$ ◆ [16]).

$$\frac{dN_\mu}{dE_\mu} \approx \frac{0.14\,E^{-2.7}}{\text{cm}^2\ \text{s sr GeV}} \times \left\{ \frac{1}{1+\dfrac{1.1E_\mu\cos\theta}{115\,\text{GeV}}} + \frac{0.054}{1+\dfrac{1.1E_\mu\cos\theta}{850\,\text{GeV}}} \right\}, \tag{20.5}$$

where the two terms give the contribution of pions and charged kaons. Eq. (20.5) neglects a small contribution from charm and heavier flavors which is negligible except at very high energy [17].

The muon charge ratio reflects the excess of π^+ over π^- in the forward fragmentation region of proton initiated interactions together with the fact that there are more protons than neutrons in the primary spectrum. The charge ratio is between 1.2 and 1.3 from 250 MeV up to 100 GeV [9].

20.3.2. ***Electromagnetic component***: At the ground, this component consists of electrons, positrons, and photons primarily from electromagnetic cascades initiated by decay of neutral and charged mesons. Muon decay is the dominant source of low-energy electrons at sea level. Decay of neutral pions is more important at high altitude or when the energy threshold is high. Knock-on electrons also make a small contribution at low energy [11]. The integral vertical intensity of electrons plus positrons is very approximately 30, 6, and 0.2 $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ above 10, 100, and 1000 MeV respectively [10,18], but the exact numbers depend sensitively on altitude, and the angular dependence is complex because of the different altitude dependence of the different sources of electrons [11,18,19]. The ratio of photons to electrons plus positrons is approximately 1.3 above a GeV and 1.7 below the critical energy [19].

20.3.3. ***Protons***: Nucleons above 1 GeV/c at ground level are degraded remnants of the primary cosmic radiation. The intensity is approximately represented by Eq. (20.3) with the replacement $t \to t/\cos\theta$ for $\theta < 70°$ and an attenuation length $\Lambda = 123$ g cm^{-2}. At sea level, about 1/3 of the nucleons in the vertical direction are neutrons (up from $\approx 10\%$ at the top of the atmosphere as the n/p ratio approaches equilibrium). The integral intensity of vertical protons above 1 GeV/c at sea level is $\approx 0.9\ \text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ [10,20].

20.4. Cosmic rays underground

Only muons and neutrinos penetrate to significant depths underground. The muons produce tertiary fluxes of photons, electrons, and hadrons.

20.4.1. ***Muons***: As discussed in Section 23.9 of this *Review*, muons lose energy by ionization and by radiative processes: bremsstrahlung, direct production of e^+e^- pairs, and photonuclear interactions. The total muon energy loss may be expressed as a function of the amount of matter traversed as

$$-\frac{dE_\mu}{dX} = a + b\,E_\mu\ , \tag{20.6}$$

where a is the ionization loss and b is the fractional energy loss by the three radiation processes. Both are slowly varying functions of energy. The quantity $\epsilon \equiv a/b$ (≈ 500 GeV in standard rock) defines a critical energy below which continuous ionization loss is more important the radiative losses. Table 20.2 shows a and b values for standard rock as a function of muon energy. The second column of Table 20.2 shows the muon range in standard rock ($A = 22$, $Z = 11$, $\rho = 2.65$ g cm^{-3}). These parameters are quite sensitive to the chemical composition of the rock, which must be evaluated for each experimental location.

The intensity of muons underground can be estimated from the muon intensity in the atmosphere and their rate of energy loss. To the extent that the mild energy dependence of a and b can be neglected, Eq. (20.6) can be integrated to provide the following relation between the energy $E_{\mu,0}$ of a muon at production in the atmosphere and its average energy E_μ after traversing a thickness X of rock (or ice or water):

$$E_\mu = (E_{\mu,0} + \epsilon)\,e^{-bX} - \epsilon\ . \tag{20.7}$$

Table 20.2: Average muon range R and energy loss parameters calculated for standard rock. Range is given in km-water-equivalent, or 10^5 g cm^{-2}.

E_μ	R	a	b_{pair}	b_{brems}	b_{nucl}	$\sum b_i$
GeV	km.w.e.	MeV g^{-1} cm^2	——	10^{-6} g^{-1} cm^2		——
10	0.05	2.15	0.73	0.74	0.45	1.91
100	0.41	2.40	1.15	1.56	0.41	3.12
1000	2.42	2.58	1.47	2.10	0.44	4.01
10000	6.30	2.76	1.64	2.27	0.50	4.40

Especially at high energy, however, fluctuations are important and an accurate calculation requires a simulation that accounts for stochastic energy-loss processes [21].

Fig. 20.5 shows the vertical muon intensity versus depth. In constructing this "depth-intensity curve," each group has taken account of the angular distribution of the muons in the atmosphere, the map of the overburden at each detector, and the properties of the local medium in connecting measurements at various slant depths and zenith angles to the vertical intensity. Use of data from a range of angles allows a fixed detector to cover a wide range of depths. The flat portion of the curve is due to muons produced locally by charged-current interactions of ν_μ.

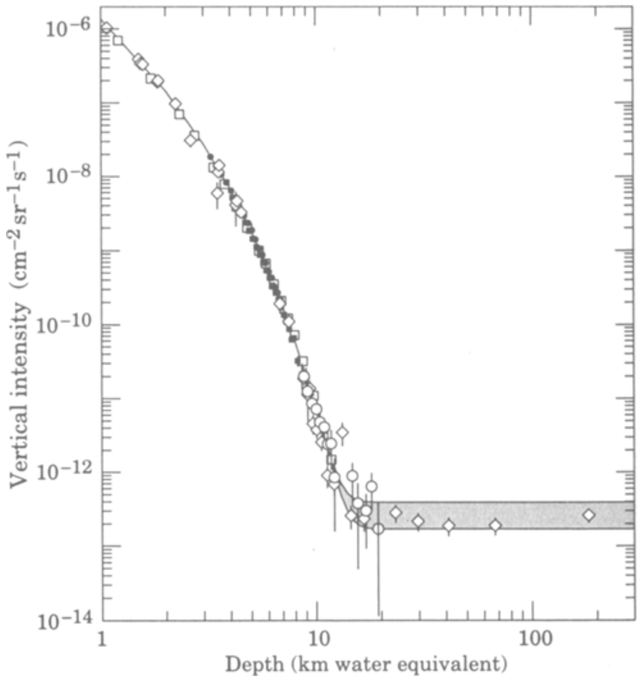

Figure 20.5: Vertical muon intensity *vs.* depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: ◊: the compilations of Crouch [29], □: Baksan [30], ○ : LVD [31], ● : MACRO [32], ■: Frejus [33]. The shaded area at large depths represents neutrino induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

The energy spectrum of atmospheric muons underground can be estimated from Eq. (20.7). The muon energy spectrum at slant depth X is

$$\frac{dN_\mu(X)}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}}\,e^{bX}\ , \tag{20.8}$$

where $E_{\mu,0}$ is the solution of Eq. (20.7). For $X \ll b^{-1} \approx 2.5$ km water equivalent, $E_{\mu,0} \approx E_\mu(X) + aX$. Thus at shallow depths the differential muon energy spectrum is approximately constant for $E_\mu < aX$ and steepens to reflect the surface muon spectrum for

$E_\mu > aX$. For $X \gg b^{-1}$ the differential spectrum underground is again constant for small muon energies but steepens to reflect the surface muon spectrum for $E_\mu > \epsilon \approx 0.5$ TeV. In this regime the shape is independent of depth although the intensity decreases exponentially with depth.

20.4.2. ***Neutrinos***: Because neutrinos have small interaction cross sections, measurements of atmospheric neutrinos require a deep detector to avoid backgrounds. There are two types of measurements: contained (or semi-contained) events, in which the vertex is determined to originate inside the detector, and neutrino-induced muons. The latter are muons that enter the detector from zenith angles so large (*e.g.*, nearly horizontal or upward) that they cannot be muons produced in the atmosphere. In neither case is the neutrino flux measured directly. What is measured is a convolution of the neutrino flux and cross section with the properties of the detector (which includes the surrounding medium in the case of entering muons).

Contained events reflect the neutrinos in the GeV region where the product of increasing cross section and decreasing flux is maximum. In this energy region the neutrino flux and its angular distribution depend on the geomagnetic location of the detector and to a lesser extent on the phase of the solar cycle. Naively, we expect $\nu_\mu/\nu_e = 2$ from counting the neutrinos of the two flavors coming from the chain of pion and muon decay. This ratio is only slightly modified by the details of the decay kinematics. Experimental measurements have also to account for the ratio of $\overline{\nu}/\nu$, which have cross sections different by a factor of 3 in this energy range. In addition, detectors will generally have different efficiencies for detecting muon neutrinos and electron neutrinos. Even after correcting for these and other effects, some detectors [22,23] infer a ν_μ/ν_e ratio lower by $\approx 4\sigma$ from the expected value. (See Tables in the Particle Listings of this *Review*.) This effect is sometimes cited as possible evidence of neutrino oscillations and is a subject of current investigation. Figure 20.6 shows the data of Refs. 22,23 for the distributions of visible energy in electron-like and muon-like charged-current events, which appear to be nearly equal in number. Corrections for detection efficiencies and backgrounds are insufficient to account for the difference from the expected value of two.

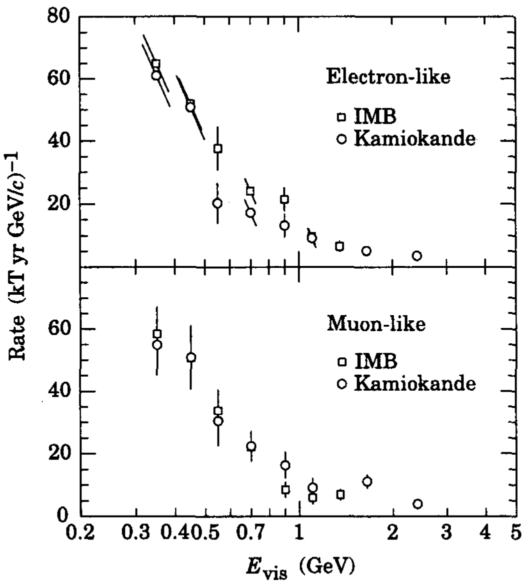

Figure 20.6: Contained neutrino interactions from IMB [23](□) and Kamiokande [22].

Muons that enter the detector from outside after production in charged-current interactions of neutrinos naturally reflect a higher energy portion of the neutrino spectrum than contained events because the muon range increases with energy as well as the cross section. The relevant energy range is $\sim 10 < E_\nu < 1000$ GeV, depending somewhat on angle. Like muons (see Eq. (20.5)), high energy neutrinos show a "secant theta" effect which causes the flux of horizontal neutrino induced muons to be approximately a factor two higher than the vertically upward flux. The upper and lower edges of the horizontal shaded region in Fig. 20.5 correspond to horizontal and vertical intensities of neutrino-induced muons. Table 20.3 gives the measured fluxes of neutrino induced muons.

Table 20.3: Measured fluxes (10^{-13} cm^{-2} s^{-1} sr^{-1}) of neutrino-induced muons as a function of the minimum muon energy E_μ.

$E_\mu >$	1 GeV	1 GeV	1 GeV	2 GeV	3 GeV
Ref.	CWI [24]	Baksan [25]	MACRO [26]	IMB [27]	Kam [28]
F_μ	2.17±0.21	2.77±0.17	2.48 ± 0.27	2.26±0.11	2.04±0.13

20.5. Air showers

So far we have discussed inclusive or uncorrelated fluxes of various components of the cosmic radiation. An air shower is caused by a single cosmic ray with energy high enough for its cascade to be detectable at the ground. The shower has a hadronic core, which acts as a collimated source of electromagnetic subshowers, generated mostly from $\pi^0 \to \gamma\gamma$. The resulting electrons and positrons are the most numerous particles in the shower. The number of muons, produced by decays of charged mesons, is an order of magnitude lower.

Air showers spread over a large area on the ground, and arrays of detectors operated for long times are useful for studying cosmic rays with primary energy $E_0 > 100$ TeV, where the low flux makes measurements with small detectors in balloons and satellites difficult.

Greisen [46] gives the following approximate expressions for the numbers and lateral distributions of particles in showers at ground level. The total number of muons N_μ with energies above 1 GeV is

$$N_\mu(> 1\ \text{GeV}) \approx 0.95 \times 10^5 \left(\frac{N_e}{10^6}\right)^{3/4} , \tag{20.9}$$

where N_e is the total number of charged particles in the shower (not just $e^\pm$). The number of muons per square meter, ρ_μ, as a function of the lateral distance r (in meters) from the center of the shower is

$$\rho_\mu = \frac{1.25\, N_\mu}{2\pi\, \Gamma(1.25)} \left(\frac{1}{320}\right)^{1.25} r^{-0.75} \left(1 + \frac{r}{320}\right)^{-2.5} , \tag{20.10}$$

where Γ is the gamma function. The number density of charged particles is

$$\rho_e = C_1(s,d,C_2)\, x^{(s-2)}(1+x)^{(s-4.5)}(1 + C_2 x^d) . \tag{20.11}$$

Here s, d, and C_2 are parameters in terms of which the overall normalization constant $C_1(s,d,C_2)$ is given by

$$C_1(s,d,C_2) = \frac{N_e}{2\pi r_1^2} [B(s, 4.5 - 2s) + C_2\, B(s+d, 4.5 - d - 2s)]^{-1} , \tag{20.12}$$

where $B(m,n)$ is the beta function. The values of the parameters depend on shower size (N_e), depth in the atmosphere, identity of the primary nucleus, etc. For showers with $N_e \approx 10^6$ at sea level, Greisen uses $s = 1.25$, $d = 1$, and $C_2 = 0.088$. Finally, x is r/r_1, where r_1 is the Molière radius, which depends on the density of the atmosphere and hence on the altitude at which showers are detected. At sea level $r_1 \approx 78$ m. It increases with altitude.

The lateral spread of a shower is determined largely by Coulomb scattering of the many low-energy electrons and is characterized by the Molìere radius. The lateral spread of the muons (ρ_μ) is larger and depends on the transverse momenta of the muons at production as well as multiple scattering.

There are large fluctuations in development from shower to shower, even for showers of the same energy and primary mass—especially for small showers, which are usually well past maximum development when observed at the ground. Thus the shower size N_e and primary energy E_0 are only related in an average sense, and even this relation depends on depth in the atmosphere. One estimate of the relation is [35]

$$E_0 \sim 3.9 \times 10^6 \text{ GeV } (N_e/10^6)^{0.9} \qquad (20.13)$$

for vertical showers with $10^{14} < E < 10^{17}$ eV at 920 g cm^{-2} (965 m above sea level). Because of fluctuations, N_e as a function of E_0 is not the inverse of Eq. (20.13). As E_0 increases the shower maximum (on average) moves down into the atmosphere and the relation between N_e and E_0 changes. At the maximum of shower development, there are approximately 2/3 particles per GeV of primary energy.

Detailed simulations and cross-calibrations between different types of detectors are necessary to establish the primary energy spectrum from air-shower experiments [35,36]. Figure 20.7 shows the "all-particle" spectrum. In establishing this spectrum, efforts have been made to minimize the dependence of the analysis on the primary composition. In the energy range above 10^{17} eV, the Fly's Eye technique [48] is particularly useful because it can establish the primary energy in a model-independent way by observing most of the longitudinal development of each shower, from which E_0 is obtained by integrating the energy deposition in the atmosphere.

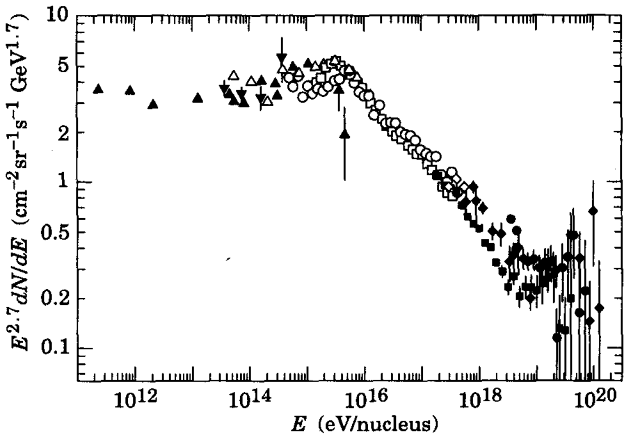

Figure 20.7: The all-particle spectrum: ▲ [37], ▼ [38], △ [39], □ [40], ○ [35], ■ [48], ● [42], ◆ [43].

In Fig. 20.7 the differential energy spectrum has been multiplied by $E^{2.7}$ in order to display the features of the steep spectrum that are otherwise difficult to discern. The steepening that occurs between 10^{15} and 10^{16} eV is known as the *knee* of the spectrum. The feature between 10^{18} and 10^{19} eV is called the *ankle* of the spectrum. Both these features are the subject of intense interest at present [44].

The *ankle* has the classical characteristic shape [45] of a higher energy population of particles overtaking a lower energy population. A possible interpretation is that the higher energy population represents cosmic rays of extragalactic origin. If this is the case and if the cosmic rays are cosmological in origin, then there should be a cutoff around 5×10^{19} eV, resulting from interactions with the microwave background [46,47]. It is therefore of special interest that several events have been assigned energies above 10^{20} eV [48,49,50].

If the cosmic ray spectrum below 10^{18} eV is of galactic origin, the *knee* could reflect the fact that some (but not all) cosmic accelerators have reached their maximum energy. Some types of expanding supernova remnants, for example, are estimated not to be able to accelerate particles above energies in the range of 10^{15} eV total energy per particle. Effects of propagation and confinement in the galaxy [51] also need to be considered.

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21. ACCELERATOR PHYSICS OF COLLIDERS

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21.1. Introduction

This article is intended to be a mini-introduction to accelerator physics, with emphasis on colliders. Essential data are summarized in the "Tables of Collider Parameters" (Sec. 22). Luminosity is the quantity of most immediate interest for HEP, and so we begin with its definition and a discussion of the various factors involved. Then we talk about some of the underlying beam dynamics. Finally, we comment on present limitations and possible future directions.

The focus is on colliders because they provide the highest c.m. energy, and so the longest potential discovery reach. All present-day colliders are synchrotrons with the exception of the SLAC Linear Collider. In the pursuit of higher c.m. energy with electrons, synchrotron radiation presents a formidable barrier to energy beyond LEP. The LHC will be the first proton collider in which synchrotron radiation has significant design impact.

21.2. Luminosity

The event rate R in a collider is proportional to the interaction cross section $\sigma_{\rm int}$ and the factor of proportionality is called the *luminosity*:

$$R = \mathscr{L}\sigma_{\rm int} \ . \tag{21.1}$$

If two bunches containing n_1 and n_2 particles collide with frequency f, then the luminosity is

$$\mathscr{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y} \tag{21.2}$$

where σ_x and σ_y characterize the Gaussian transverse beam profiles in the horizontal (bend) and vertical directions. Though the initial distribution at the source may be far from Gaussian, by the time the beam reaches high energy the normal form is a very good approximation thanks to the central limit theorem of probability and diminished importance of space charge effects.

Luminosity is normally expressed in units of cm^{-2}s^{-1}, and tends to be a large number; the highest instantaneous luminosity achieved to date is about 4.5×10^{32} cm^{-2}s^{-1} at CESR, and for protons, 2.3×10^{32} cm^{-2}s^{-1} at the now-decommissioned ISR. The critical quantity for HEP is the integrated luminosity, often stated in pb^{-1}. For example, during the most-recent two-year Tevatron run, an integrated luminosity of 150 pb^{-1} was obtained.

The beam size can be expressed in terms of two quantities, one termed the *transverse emittance*, ϵ and the other, the *amplitude function*, β. The transverse emittance is a beam quality concept reflecting the process of bunch preparation, extending all the way back to the source for hadrons and, in the case of electrons, mostly dependent on synchrotron radiation. The amplitude function is a beam optics quantity and is determined by the accelerator magnet configuration.

The transverse emittance is a measure of the phase space area associated with either of the two transverse degrees of freedom, x and y. These coordinates represent the position of a particle with reference to some ideal design trajectory. Think of x as the "horizontal" displacement (in the bend plane for the case of a synchrotron), and y as the "vertical" displacement. The conjugate coordinates are the transverse momenta, which at constant energy are proportional to the angles of particle motion with respect to the design trajectory, x' and y'. Various conventions are in use to characterize the boundary of phase space. Beam sizes are usually given as the standard deviations characterizing Gaussian beam profiles in the two transverse degrees of freedom. In each degree of freedom, the one-σ contour in displacement and angle is frequently used and we will follow this choice.

Suppose that at some location in the collider, the phase space boundary appears as an upright ellipse where the coordinates are the displacement x (using the horizontal plane for instance) and the angle x' with respect to the beam axis. The choice of an elliptical contour will be justified under Beam Dynamics below. If σ and σ' are the ellipse semi-axes in the x and x' directions respectively, then the emittance may be defined by $\epsilon \equiv \pi\sigma\sigma'$. Transverse emittance is often stated in units of mm-mrad.

The aspect ratio, σ/σ', is the so-called *amplitude function*, β, and its value depends on position within the focussing structure. When expressed in terms of σ and β the transverse emittance becomes

$$\epsilon = \pi\frac{\sigma^2}{\beta} \ . \tag{21.3}$$

Of particular significance is the value of the amplitude function at the interaction point, β^*. To achieve high luminosity, one wants β^* to be as small as possible; how small depends on the capability of the hardware to make a near-focus at the interaction point. For example, in the HERA proton ring, β^* at one of the major detectors is 1 m while elsewhere in the synchrotron typical values of the amplitude function lie in the range 30–100 m.

Eq. (21.2) can now be recast in terms of emittances and amplitude functions as

$$\mathscr{L} = f\frac{n_1 n_2}{4\sqrt{\epsilon_x\beta_x^*\,\epsilon_y\beta_y^*}} \ . \tag{21.4}$$

Thus, to achieve high luminosity, all one has to do is make high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible.

Depending on the particular facility, there are other ways of stating the expression for the luminosity. In a multibunch collider, the various bunch populations will differ, in a facility such as HERA, the electron and proton bunches may differ in emittance, the variation of the beam size in the neighborhood of the interaction point may be significant, and so on.

21.3. Beam dynamics

A major concern of beam dynamics is stability: conservation of adequate beam properties over a sufficiently long time scale. Several time scales are involved, and the approximations used in writing the equations of motion reflect the time scale under consideration. For example, when, in Sec. 21.3.1 below, we write the equations for transverse stability no terms associated with phase stability or synchrotron radiation appear; the time scale associated with the last two processes is much longer than that demanded by the need for transverse stability.

21.3.1. ***Betatron oscillations***: Present-day high-energy accelerators employ alternating gradient focussing provided by quadrupole magnetic fields [1]. The equations of motion of a particle undergoing oscillations with respect to the design trajectory are

$$x'' + K_x(s)\,x = 0 \ , \quad y'' + K_y(s)\,y = 0 \ , \tag{21.5}$$

with

$$x' \equiv dx/ds \ , \quad y' \equiv dy/ds \tag{21.6}$$

$$K_x \equiv B'/(B\rho) + \rho^{-2} \ , \quad K_y \equiv -B'/(B\rho) \tag{21.7}$$

$$B' \equiv \partial B_y/\partial x \ . \tag{21.8}$$

The independent variable s is path length along the design trajectory. This motion is called a *betatron* oscillation because it was initially studied in the context of that type of accelerator. The functions K_x and K_y reflect the transverse focussing—primarily due to quadrupole fields except for the radius of curvature, ρ, term in K_x for a synchrotron—so each equation of motion resembles that for a harmonic oscillator but with spring constants that are a function of position. No terms relating to synchrotron oscillations appear, because their time scale is much longer and in this approximation play no role.

These equations have the form of Hill's equation and so the solution in one plane may be written as

$$x(s) = A\sqrt{\beta(s)}\,\cos(\psi(s) + \delta), \tag{21.9}$$

where A and δ are constants of integration and the phase advances according to $d\psi/ds = 1/\beta$. The dimension of A is the square root of length, reflecting the fact that the oscillation amplitude is modulated by the square root of the amplitude function. In addition to describing the envelope of the oscillation, β also plays the role of an 'instantaneous' $\bar{\lambda}$. The wavelength of a betatron oscillation may be some tens of meters, and so typically values of the amplitude function are of the order of meters rather than on the order of the beam size. The beam optics arrangement generally has some periodicity and the amplitude function is chosen to reflect that periodicity. As noted above, at the interaction point a small value of the amplitude function is desired, and so the focussing optics is tailored in the neighborhood to provide a suitable β^*.

The number of betatron oscillations per turn in a synchrotron is called the *tune* and is given by

$$\nu = \frac{1}{2\pi}\oint\frac{ds}{\beta}\ . \qquad (21.10)$$

Expressing the integration constant A in the solution above in terms of x, x' yields the *Courant-Snyder invariant*

$$A^2 = \gamma(s)\,x(s)^2 + 2\alpha(s)\,x(s)\,x'(s) + \beta(s)\,x'(s)^2$$

where

$$\alpha \equiv -\beta'/2,\ \ \gamma \equiv \frac{1+\alpha^2}{\beta}\ . \qquad (21.11)$$

(The Courant-Snyder parameters α, β and γ employ three Greek letters which have other meanings and the significance at hand must often be recognized from context.) Because β is a function of position in the focussing structure, this ellipse changes orientation and aspect ratio from location to location but the area πA^2 remains the same.

As noted above the transverse emittance is a measure of the area in x, x' (or y, y') phase space occupied by an ensemble of particles. The definition used in Eq. (21.3) is the area that encloses 39% of a Gaussian beam.

For electron synchrotrons the equilibrium emittance results from the balance between synchrotron radiation damping and excitation from quantum fluctuations in the radiation rate. The equilibrium is reached in a time small compared with the storage time.

For present-day hadron synchrotrons, synchrotron radiation does not play a similar role in determining the transverse emittance. Rather the emittance during storage reflects the source properties and the abuse suffered by the particles throughout acceleration and storage. Nevertheless it is useful to argue as follows: Though x' and x can serve as canonically conjugate variables at constant energy this definition of the emittance would not be an adiabatic invariant when the energy changes during the acceleration cycle. However, $\gamma(v/c)x'$, where here γ is the Lorentz factor, is proportional to the transverse momentum and so qualifies as a variable conjugate to x. So often one sees a normalized emittance defined according to

$$\epsilon_N = \gamma\frac{v}{c}\,\epsilon. \qquad (21.12)$$

21.3.2. ***Phase stability*:** The particles in a circular collider also undergo synchrotron oscillations. This is usually referred to as motion in the *longitudinal* degree-of-freedom because particles arrive at a particular position along the accelerator earlier or later than an ideal reference particle. This circumstance results in a finite bunch length, which is related to an energy spread.

For dynamical variables in longitudinal phase space, let us take ΔE and Δt, where these are the energy and time differences from that of the ideal particle. A positive Δt means a particle is behind the ideal particle. The equation of motion is the same as that for a physical pendulum and therefore is nonlinear. But for small oscillations, it reduces to a simple harmonic oscillator:

$$\frac{d^2\Delta t}{dn^2} = -(2\pi\nu_s)^2\Delta t \qquad (21.13)$$

where the independent variable n is the turn number and ν_s is the number of synchrotron oscillations per turn, analogous to the betatron oscillation tune defined earlier.

In the high-energy limit, where $v/c \approx 1$,

$$\nu_s = \left[\frac{h\eta\, eV\,\cos\phi_s}{2\pi E}\right]^{1/2}\ . \qquad (21.14)$$

There are four as yet undefined quantities in this expression: the harmonic number h, the slip factor η, the maximum energy eV gain per turn from the acceleration system, and the synchronous phase ϕ_s. The frequency of the RF system is normally a relatively high multiple, h, of the orbit frequency. The slip factor relates the fractional change in the orbit period τ to changes in energy according to

$$\frac{\Delta\tau}{\tau} = \eta\frac{\Delta E}{E}\ . \qquad (21.15)$$

At sufficiently high energy, the slip factor just reflects the relationship between path length and energy, since the speed is a constant; η is positive for all the synchrotrons in the tables.

The synchronous phase is a measure of how far up on the RF wave the average particle must ride in order to maintain constant energy in the face of synchrotron radiation. That is, $\sin\phi_s$ is the ratio of the energy loss per turn to the maximum energy per turn that can be provided by the acceleration system. For hadron colliders built to date, $\sin\phi_s$ is effectively zero. This is not the case for electron storage rings; for example, the electron ring of HERA runs at a synchronous phase of 45°.

Now if one has a synchrotron oscillation with amplitudes $\widehat{\Delta t}$ and $\widehat{\Delta E}$,

$$\Delta t = \widehat{\Delta t}\,\sin(2\pi\nu_s n)\ ,\qquad \Delta E = \widehat{\Delta E}\,\cos(2\pi\nu_s n) \qquad (21.16)$$

then the amplitudes are related according to

$$\widehat{\Delta E} = \frac{2\pi\nu_s E}{\eta\tau}\widehat{\Delta t}\ . \qquad (21.17)$$

The longitudinal emittance ϵ_ℓ may be defined as the phase space area bounded by particles with amplitudes $\widehat{\Delta t}$ and $\widehat{\Delta E}$. In general, the longitudinal emittance for a given amplitude is found by numerical integrations. For $\sin\phi_s = 0$, an analytical expression is as follows:

$$\epsilon_\ell = \left[\frac{2\pi^3 EeVh}{\tau^2\eta}\right]^{1/2}(\widehat{\Delta t})^2 \qquad (21.18)$$

Again, a Gaussian is a reasonable representation of the longitudinal profile of a well-behaved beam bunch; if $\sigma_{\Delta t}$ is the standard deviation of the time distribution, then the bunch length can be characterized by

$$\ell = c\,\sigma_{\Delta t}\ . \qquad (21.19)$$

In the electron case the longitudinal emittance is determined by the synchrotron radiation process just as in the transverse degrees of freedom. For the hadron case the history of acceleration plays a role and because energy and time are conjugate coordinates, the longitudinal emittance is a quasi-invariant.

For HEP bunch length is a significant quantity because if the bunch length becomes larger than β^* the luminosity is adversely affected. This is because β grows parabolically as one proceeds from the IP and so the beam size increases thus lowering the contribution to the luminosity from such locations.

21.3.3. ***Synchrotron radiation*** [2]: A relativistic particle undergoing centripetal acceleration radiates at a rate given by the Larmor formula multiplied by the 4th power of the Lorentz factor:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4. \qquad (21.20)$$

Here, $a = v^2/\rho$ is the centripetal acceleration of a particle with speed v undergoing deflection with radius of curvature ρ. In a synchrotron that has a constant radius of curvature within bending magnets, the energy lost due to synchrotron radiation per turn is the above multiplied by the time spent in bending magnets, $2\pi\rho/v$. Expressed in familiar units, this result may be written

$$W = 8.85 \times 10^{-5} \frac{E^4}{\rho} \text{ MeV per turn} \tag{21.21}$$

for electrons at sufficiently high energy that $v \approx c$. The energy E is in GeV and ρ is in kilometers.

The characteristic time for synchrotron radiation processes is the time during which the energy must be replenished by the acceleration system. If f_0 is the orbit frequency, then the characteristic time is given by

$$\tau_0 = \frac{E}{f_0 W} \ . \tag{21.22}$$

Oscillations in each of the three degrees of freedom either damp or antidamp depending on the design of the accelerator. For a simple separated function alternating gradient synchrotron, all three modes damp. The damping time constants are related by Robinson's Theorem [3], which, expressed in terms of τ_0, is

$$\frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_s} = 2\frac{1}{\tau_0} \ . \tag{21.23}$$

Even though all three modes may damp, the emittances do not tend toward zero. Statistical fluctuations in the radiation rate excite synchrotron oscillations and radial betatron oscillations. Thus there is an equilibrium emittance at which the damping and excitation are in balance. The vertical emittance is non-zero due to horizontal-vertical coupling.

The radiation rate for protons is of course down by a factor of the fourth power of the mass ratio, and is given by

$$W = 7.8 \times 10^{-3} \frac{E^4}{\rho} \text{ keV per turn} \tag{21.24}$$

where E is now in TeV and ρ in km. As noted in the Introduction, the LHC will the first proton facility in which synchrotron radiation plays a significant role.

21.3.4. ***Beam-beam tune shift***: In a bunch-bunch collision the particles of one bunch see the other bunch as a nonlinear lens. Therefore the focussing properties of the ring are changed in a way that depends on the transverse oscillation amplitude. And so there is a spread in the frequency of betatron oscillations.

There is an extensive literature on the subject of how large this tune spread can be. In practice, the limiting value is hard to predict. It is consistently larger for electrons because of the beneficial effects of damping from synchrotron radiation.

In order that contributions to the total tune spread arise only at the detector locations, the beams in a multibunch collider are kept apart elsewhere by a variety of techniques. For equal energy particles of opposite charge circulating in the same vacuum chamber, electrostatic separators may be used assisted by a crossing angle if appropriate. For particles of equal energy and of the same charge, a crossing angle is needed not only for tune spread reasons but to steer the particles into two separate beam pipes. In HERA, because of the large ratio of proton to electron energy, separation can be achieved by bending magnets.

21.3.5. ***Luminosity lifetime***: In electron synchrotrons the luminosity degrades during the store primarily due to particles leaving the phase stable region in longitudinal phase space as a result of quantum fluctuations in the radiation rate and bremsstrahlung. For hadron colliders the luminosity deteriorates due to emittance dilution resulting from a variety of processes. In practice, stores are intentionally terminated when the luminosity drops to the point where a refill will improve the integrated luminosity.

21.4. Status and prospects

Present facilities represent a balance between available technology and the desires of High Energy Physics. For forty-five years, beam optics has exploited the invention of alternating gradient focussing. This principle is employed in all colliders both linear and circular. Superconducting technology has grown dramatically in importance during the last two decades. Superconducting magnets are vital to the Tevatron, HERA, and to the future LHC. Superconducting accelerating structures are necessary to CESR, LEP, HERA, Jefferson Laboratory and other facilities requiring high-gradient long pulse length RF systems. Present room temperature accelerating structures produce very short pulses, but with gradients well in excess of the superconducting variety [7].

At present, the next potential facilities are perceived to include the LHC and an electron linear collider. The LHC is an approved project that will represent a major step forward in superconducting magnet technology. No linear collider project has been approved as yet, and the conventional and superconducting approaches compete for prominence. Of perhaps more immediate impact are the B and τ "factories" that are designed to go beyond the 10^{33} cm^{-2}s^{-1} level in luminosity.

In addition to the possibilities of the preceding paragraph, there are other synchrotron-based collider studies underway. Despite formidable R&D challenges a muon-muon collider may become feasible. Proponents of a very large hadron collider at higher energy than the cancelled SSC project are exploring low-cost magnets and tunnels for a facility on the 100 TeV c.m. energy scale.

Ideas abound in accelerator R&D for the long term. Approaches such as wakefield accelerators, plasma-laser combinations, and related investigations may if successful deliver gradients far higher than anything realized today. These studies could potentially lead to a new vision for HEP facilities.

References:

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HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (I)

The numbers here were received from representatives of the colliders in 1998 (contact C.G. Wohl, LBNL). Many of the numbers of course change with time, and only the latest values (or estimates) are given here; those in brackets are for coming upgrades. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions. Parameters for the defunct SPEAR, DORIS, PETRA, PEP, and TRISTAN colliders may be found in our 1996 edition (Phys. Rev. **D54**, 1 July 1996, Part I).

	VEPP-2M [round beams] (Novosibirsk)	DAΦNE (Frascati)	ϕ FACTORY (Novosibirsk)	τ-CHARM FACTORY (Novosibirsk)	BEPC (China)	VEPP-4M (Novosibirsk)
Physics start date	1974 [1998]	1998	2001	?	1989	1994
Maximum beam energy (GeV)	0.7 [0.55]	0.510 (0.75 max.)	0.55	2.1	2.2	6
Luminosity (10^{30} cm^{-2}s^{-1})	5 [100]	135(→540)	2500	10000	10 at 2 GeV	50
Time between collisions (μs)	0.03	0.0108(→0.0027)	0.007	0.027	0.8	0.6
Crossing angle (μ rad)	0	$\pm(1.0 \text{ to } 1.5)\times10^4$	0	0	0	0
Energy spread (units 10^{-3})	0.36	0.40	0.43	0.002–0.7	0.58 at 2.2 GeV	1
Bunch length (cm)	3	3.0	1	1	≈ 5	5
Beam radius (10^{-6} m)	H/V: 300/10 [90 (round)]	H: 2100 V: 21	35 (beams are round)	33	H: 890 V: 37	H: 1000 V: 30
Free space at interaction point (m)	±1	±0.46 (±157 mrad cone)	±2	±1.5	±2.15	±2
Luminosity lifetime (hr)	continuous	2	continuous	continuous	7–12	2
Filling time (min)	continuous	3 (topping up)	continuous	continuous	30	15
Acceleration period (s)	—	—	—	—	120	150
Injection energy (GeV)	0.2–0.6 [0.2–0.55]	0.510	—	2.1	1.55	1.8
Transverse emittance ($10^{-9}\pi$ rad-m)	H/V: 110/1.3 [170]	H: 1000 V: 10	125	H: 100–10000 V: 1–10000	H: 660 V: 28	H: 400 V: 20
β^*, amplitude function at interaction point (m)	H/V: 0.45/0.045 [0.05]	H: 4.5 V: 0.045	0.01	0.01	H: 1.2 V: 0.05	H: 0.75 V: 0.05
Beam-beam tune shift per crossing (units 10^{-4})	H/V: 200/500 [1000]	400	1000	500	350	500
RF frequency (MHz)	200	368.25	700	700	199.53	180
Particles per bunch (units 10^{10})	2 [6.7]	8.9	5	20	20 at 2 GeV	15
Bunches per ring per species	1	30(→120)	11	95	1	2
Average beam current per species (mA)	50 [160]	1313(→5250)	550	1120	40 at 2 GeV	80
Circumference or length (km)	0.018	0.0977	0.047	0.773	0.2404	0.366
Interaction regions	2	2	1	1	2	1
Utility insertions	1	2 × 2	1	1	4	1
Magnetic length of dipole (m)	1	e^+: 1.21/0.99 e^-: 1.21/0.99	0.8	1.47	1.6	2
Length of standard cell (m)	4.5 [9.0]	—	—	5	6.6	7.2
Phase advance per cell (deg)	280 [560]	—	—	60	≈ 60	65
Dipoles in ring	8	e^+: 8(+4 wigglers) e^-: 8(+4 wigglers)	22	112	40 + 4 weak	78
Quadrupoles in ring	20 [12]	e^+/e^-: 53/53	22	112	68	150
Peak magnetic field (T)	1.8 [1.5]	1.2(→1.76) dipoles 1.8 wigglers	1.8	0.13	0.9028 at 2.8 GeV	0.6

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (II)

The numbers here were received from representatives of the colliders in 1998. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions; s.c. indicates superconducting.

	CESR (Cornell)	KEKB (KEK)	PEP-II (SLAC)	SLC (SLAC)	LEP (CERN)
Physics start date	1979	1999	1999	1989	1989
Maximum beam energy (GeV)	6	$e^- \times e^+$: 8×3.5	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 ") (nominal $E_{\rm cm}$ = 10.5 GeV)	50	92 in 1997 (100=max. foreseen)
Luminosity (10^{30} cm^{-2}s^{-1})	470 at 5.3 GeV	10000	3000	2.5	24 at Z^0 50 at > 90 GeV
Time between collisions (μs)	0.028 to 0.22	0.002	0.0042	8300	22
Crossing angle (μ rad)	±2000	±11,000	0	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.7	e^-/e^+: 0.61/0.77	1.2	1.0
Bunch length (cm)	1.8	0.4	e^-/e^+: 1.1/1.0	0.1	1.0
Beam radius (μm)	H: 500 V: 10	H: 77 V: 1.9	H: 181 V: 5.4	H: 1.5 V: 0.5	H: 200 V: 8
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	+0.75/−0.58 (+300/−500) mrad cone	±0.2, ±300 mrad cone	±2.8	±3.5
Luminosity lifetime (hr)	3–4	2	2.5	—	20 at Z^0 10 at > 90 GeV
Filling time (min)	10 (topping up)	8 (topping up)	3 (topping up)	—	20 to setup 20 to accumulate
Acceleration period (s)	—	—	—	—	550
Injection energy (GeV)	6	e^-/e^+: 8/3.5	2.5–12	45.64	22
Transverse emittance (π rad-nm)	H: 240 V: 6	H: 18 V: 0.36	e^-: 48 (H), 1.5 (V) e^+: 64 (H), 2.0 (V)	H: 0.5 V: 0.05	H: 35 V: 0.25 → 1
β^*, amplitude function at interaction point (m)	H: 1.0 V: 0.018	H: 0.33 V: 0.01	e^-: 0.67 (H), 0.02 (V) e^+: 0.50 (H), 0.015 (V)	H: 0.0025 V: 0.0015	H: 1.5 V: 0.05
Beam-beam tune shift per crossing (units 10^{-4})	420	H: 390 V: 520	300	—	500
RF frequency (MHz)	500	508.887	476	—	352.2
Particles per bunch (units 10^{10})	15	e^-/e^+: 1.3/3.2	e^-/e^+: 2.7/5.9	4.0	30 in collision 60 in single beam
Bunches per ring per species	9 trains of 2 bunches	5120	1658	1	4 trains of 1 or 2
Average beam current per species (mA)	180	e^-/e^+: 1100/2600	e^-/e^+: 995/2161	0.0008	4 at Z^0 2.5 at > 90 GeV
Beam polarization (%)	—	—	—	e^-: 80	55
Circumference or length (km)	0.768	3.016	2.2	1.45 +1.47	26.66
Interaction regions	1	1	1 (2 possible)	1	4
Utility insertions	3	3	5	—	4
Magnetic length of dipole (m)	1.6–6.6	e^-/e^+: 5.86/0.915	e^-/e^+: 5.4/0.45	2.5	11.66/pair
Length of standard cell (m)	16	e^-/e^+: 75.7/76.1	15.2	5.2	79
Phase advance per cell (deg)	45–90 (no standard cell)	450	e^-/e^+: 60/90	108	90/60
Dipoles in ring	86	e^-/e^+: 116/112	e^-/e^+: 192/192	460+440	3280+24 inj. + 64 weak
Quadrupoles in ring	104	e^-/e^+: 452/452	e^-/e^+: 290/326	—	520+288 + 8 s.c.
Peak magnetic field (T)	0.3 normal } at 8 0.8 high field } GeV	e^-/e^+: 0.25/0.72	e^-/e^+: 0.18/0.75	0.597	0.135

HIGH-ENERGY COLLIDER PARAMETERS: ep, $\bar{p}p$, and pp Colliders

The numbers here were received from representatives of the colliders in 1998. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. H, V, and, s.c. indicate horizontal and vertical directions, and superconducting. The SSC is kept for purposes of comparison.

	HERA (DESY)	$Sp\bar{p}S$ (CERN)	TEVATRON[†] (Fermilab)	LHC (CERN)		SSC (USA)
Physics start date	1992	1981	1987	2005		Terminated
Physics end date	—	1990	—	—		—
Particles collided	ep	$p\bar{p}$	$p\bar{p}$	pp	Pb Pb	pp
Maximum beam energy (TeV)	e: 0.030 p: 0.82	0.315 (0.45 in pulsed mode)	1.0	7.0	2.76 TeV/u	20
Luminosity $(10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$	14	6	210	1.0×10^4	0.002	1000
Time between collisions (μs)	0.096	3.8	0.396	0.025	0.125	0.016678
Crossing angle (μ rad)	0	0	0	≥ 200	≤ 200	100 to 200 (135 nominal)
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.35	0.09	0.1	0.1	0.055
Bunch length (cm)	e: 0.83 p: 8.5	20	38	7.5	7.5	6.0
Beam radius (10^{-6} m)	e: 280(H), 50(V) p: 265(H), 50(V)	p: 73(H), 36(V) $\bar{p}$: 55(H), 27(V)	p: 34 $\bar{p}$: 29	16	15	4.8
Free space at interaction point (m)	±5.8	16	±6.5	38	38	±20
Luminosity lifetime (hr)	10	15	7–30	10	6.7	~24
Filling time (min)	e: 60 p: 120	0.5	30	6	20	72
Acceleration period (s)	e: 200 p: 1500	10	86	1200		1500
Injection energy (TeV)	e: 0.012 p: 0.040	0.026	0.15	0.450	177.4 GeV/u	2
Transverse emittance ($10^{-9}\pi$ rad-m)	e: 42(H), 6(V) p: 5(H), 5(V)	p: 9 $\bar{p}$: 5	p: 3.5 $\bar{p}$: 2.5	0.5	0.5	0.047
β^*, amplitude function at interaction point (m)	e: 1(H), 0.7(V) p: 7(H), 0.5(V)	0.6 (H) 0.15 (V)	0.35	0.5	0.5	0.5
Beam-beam tune shift per crossing (units 10^{-4})	e: 190(H), 360(V) p: 12(H), 9(V)	50	p: 38 $\bar{p}$: 97	34	—	8 head on 13 long range
RF frequency (MHz)	e: 499.7 p: 208.2/52.05	100+200	53	400.8	400.8	359.75
Particles per bunch (units 10^{10})	e: 3 p: 7	p: 15 $\bar{p}$: 8	p: 27 $\bar{p}$: 7.5	10.5	0.0094	0.8
Bunches per ring per species	e: 189 p: 180	6	36	2835	608	17,424
Average beam current per species (mA)	e: 40 p: 90	p: 6 $\bar{p}$: 3	p: 81 $\bar{p}$: 22	536	7.8	71
Circumference (km)	6.336	6.911	6.28	26.659		87.12
Interaction regions	ep: 2; e,p: 1 each, internal fixed target	2	2 high $\mathscr{L}$	2 high $\mathscr{L}$ +1	1	4
Utility insertions	4	—	4	4		2
Magnetic length of dipole (m)	e: 9.185 p: 8.82	6.26	6.12	14.3		Mostly 14.928
Length of standard cell (m)	e: 23.5 p: 47	64	59.5	106.90		180
Phase advance per cell (deg)	e: 60 p: 90	90	67.8	90		90
Dipoles in ring	e: 396 p: 416	744	774	1232 main dipoles		H: 8336 V: 88 } in 2 rings
Quadrupoles in ring	e: 580 p: 280	232	216	692 focussing +96 skew		2084 } 2 rings
Magnet type	e: C-shaped p: s.c., collared, cold iron	H type with bent-up coil ends	s.c. $\cos\theta$ warm iron	s.c. 2 in 1 cold iron		s.c. $\cos\theta$ cold iron
Peak magnetic field (T)	e: 0.274 p: 4.65	1.4 (2 in pulsed mode)	4.4	8.3		6.790
$\bar{p}$ source accum. rate (hr^{-1})	—	6×10^{10}	20×10^{10}	—		—
Max. no. $\bar{p}$ in accum. ring	—	1.2×10^{12}	2.6×10^{12}	—		—

[†] TEVATRON numbers are for the year 2000, when it again runs in collider mode.

23. PASSAGE OF PARTICLES THROUGH MATTER

Revised May 1998 by D.E. Groom (LBNL).

23.1. Notation

Table 23.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

Symbol	Definition	Units or Value
α	Fine structure constant	$1/137.035\,989\,5(61)$
M	Incident particle mass	MeV/c^2
E	Incident particle energy $\gamma M c^2$	MeV
T	Kinetic energy	MeV
$m_e c^2$	Electron mass × c^2	$0.510\,999\,06(15)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,92(38)$ fm
N_A	Avogadro's number	$6.022\,136\,7(36) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of medium	
A	Atomic mass of medium	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_e c^2/A$	$0.307\,075$ MeV g^{-1} cm^2 for $A = 1$ g mol^{-1}
I	Mean excitation energy	eV
δ	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $\sqrt{4\pi N_e r_e^3}\, m_e c^2/\alpha$	$28.816\sqrt{\rho\langle Z/A\rangle}$ eV$^{(a)}$
N_c	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
X_0	Radiation length	g cm^{-2}
—	$4\alpha r e^2 N_A/A$	$(716.408$ g cm$^{-2})^{-1}$ for $A = 1$ g mol^{-1}
E_c	Critical energy	MeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\, m_e c^2$	21.2052 MeV
R_M	Molière radius	MeV g^{-1} cm^2

$^{(a)}$ For ρ in g cm^{-3}.

23.2. Ionization energy loss by heavy particles [1–5]

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization. The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right] . \tag{23.1}$$

Here $T_{\max}$ is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 23.1. The units are chosen so that dx is measured in mass per unit area, *e.g.*, in g cm^{-2}.

In this form, the Bethe-Bloch equation describes the energy loss of pions in a material such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV. At lower energies corrections for tightly-bound atomic electrons and other effects must be made, and at higher energies radiative effects begin to be important. These limits of validity depend on both the effective atomic number of the absorber and the mass of the slowing particle. Low-energy effects will be discussed in Sec. 23.2.2.

The function as computed for pions on copper is shown by the solid curve in Fig. 23.1, and for pions on other materials in Fig. 23.2. A minor dependence on M at the highest energies is introduced through $T_{\max}$, but for all practical purposes in high-energy physics dE/dx in a given material is a function only of β. Except in hydrogen, particles of the same velocity have very similar rates of energy loss in different materials; there is a slow decrease in the rate of energy loss with increasing Z. The qualitative difference in stopping power behavior at high energies between a gas (He) and the other materials shown in Fig. 23.2 is due to the density-effect correction, δ, discussed below.

The stopping power functions are characterized by broad minima whose position drops from $\beta\gamma = 3.5$ to 3.0 as Z goes from 7 to 100.

In practical cases, most relativistic particles (*e.g.*, cosmic-ray muons) have energy loss rates close to the minimum, and are said to be minimum ionizing particles, or mip's.

Eq. (23.1) may be integrated to find the total range R for a particle which loses energy only through ionization. Since dE/dx depends only on β, R/M is a function of E/M or pc/M. In practice, range is a useful concept only for low-energy hadrons ($R \lesssim \lambda_I$, where λ_I is the nuclear interaction length), and for muons below a few hundred GeV (above which radiative effects dominate). R/M as a function of $\beta\gamma = pc/M$ is shown for a variety of materials in Fig. 23.3.

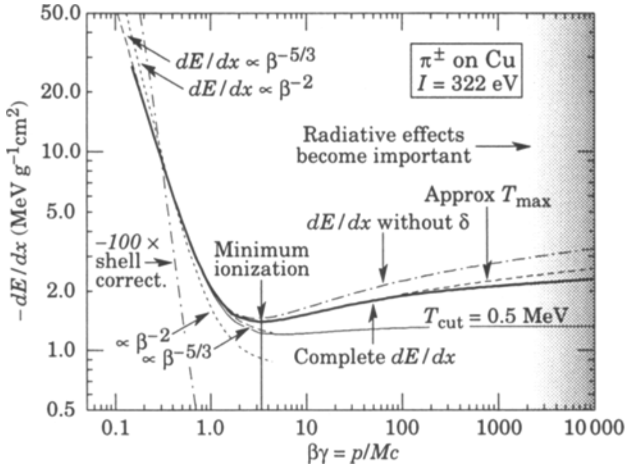

Figure 23.1: Energy loss rate in copper. The function without the density-effect correction, δ, is also shown, as is the loss rate excluding energy transfers with $T > 0.5$ MeV. The shell correction is indicated. The conventional β^{-2} low-energy approximation is compared with $\beta^{-5/3}$.

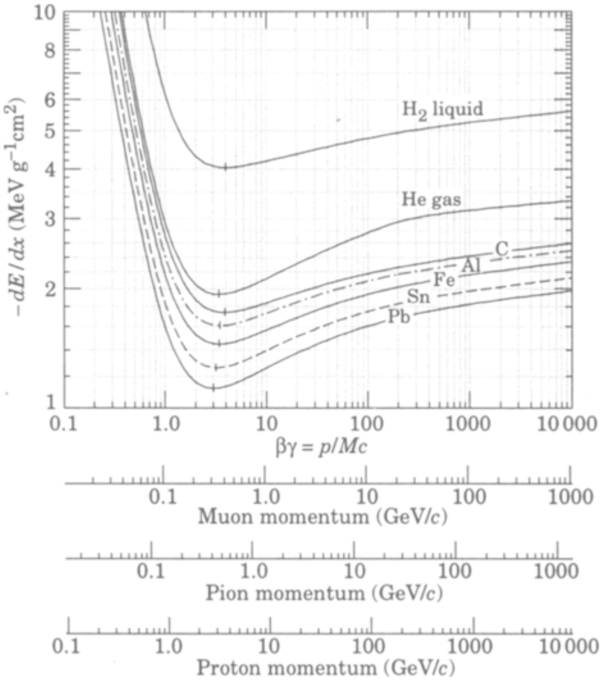

Figure 23.2: Energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, tin, and lead.

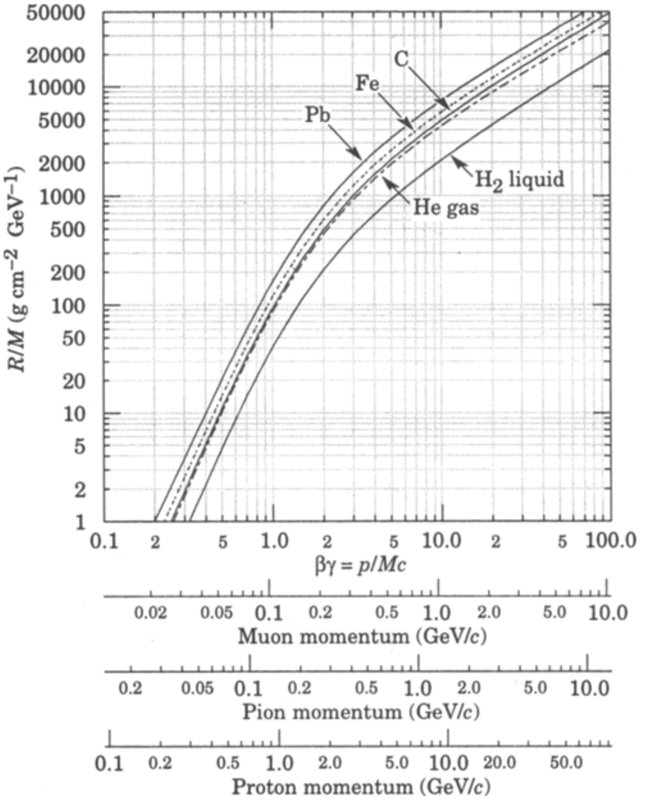

Figure 23.3: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2}.

For a particle with mass M and momentum $M\beta\gamma c$, $T_{\rm max}$ is given by

$$T_{\rm max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} \;. \tag{23.2}$$

It is usual [1,2] to make the "low-energy" approximation $T_{\rm max} = 2m_ec^2\,\beta^2\gamma^2$, valid for $2\gamma m_e/M \ll 1$; this, in fact, is done implicitly in many standard references. For a pion in copper, the error thus introduced into dE/dx is greater than 6% at 100 GeV. The correct expression should be used.

At energies of order 100 GeV, the maximum 4-momentum transfer to the electron can exceed 1 GeV/c, where structure effects significantly modify the cross sections. This problem has been investigated by J.D. Jackson [6], who concluded that for hadrons (but not for large nuclei) corrections to dE/dx are negligible below energies where radiative effects dominate. While the cross section for rare hard collisions is modified, the average stopping power, dominated by many softer collisions, is almost unchanged.

The mean excitation energy I is $(10 \pm 1$ eV$) \times Z$ for elements heavier than sulphur. The values adopted by the ICRU for the chemical elements [7] are now in wide use; these are shown in Fig. 23.4. Machine-readable versions can also be found [8]. Given the availability of these constants and their variation with atomic structure, there seems little point to depending upon approximate formulae, as was done in the past.

Ionization losses by electrons and positrons [7,9,10] are not discussed here. Above the critical energy, which is a few tens of MeV in most materials (see Fig. 23.7, bremsstrahlung is the dominant source of energy loss. This important case is discussed below. The contributions of various electron energy-loss processes in lead are shown in Fig. 24.4.

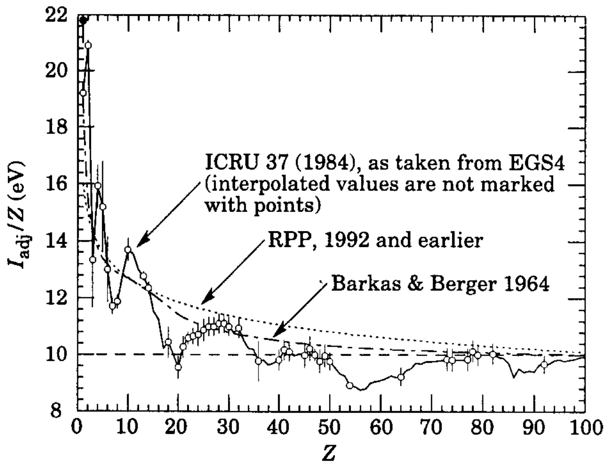

Figure 23.4: Excitation energies (divided by Z) as adopted by the ICRU [7]. Those based on measurement are shown by points with error flags; the interpolated values are simply joined. The solid point is for liquid H_2; the open point at 19.2 is for H_2 gas. Also shown are curves based on two approximate formulae.

23.2.1. ***The density effect:*** As the particle energy increases, its electric field flattens and extends, so that the distant-collision contribution to Eq. (23.1) increases as $\ln\beta\gamma$. However, real media become polarized, limiting the field extension and effectively truncating this part of the logarithmic rise [4,11–14]. At very high energies,

$$\delta/2 \to \ln(\hbar\omega_p/I) + \ln\beta\gamma - 1/2 \;, \tag{23.3}$$

where $\delta/2$ is the density effect correction introduced in Eq. (23.1) and $\hbar\omega_p$ is the plasma energy defined in Table 23.1. A comparison with Eq. (23.1) shows that $|dE/dx|$ then grows as $\ln\beta\gamma$ rather than $\ln\beta^2\gamma^2$, and that the mean excitation energy I is replaced by the plasma energy $\hbar\omega_p$. The stopping power as calculated with and without the density effect correction is shown in Fig. 23.1. Since the plasma frequency scales as the square root of the electron density, the correction is much larger for a liquid or solid than for a gas, as is illustrated by the examples in Fig. 23.2.

The density effect correction is usually computed using Sternheimer's parameterization [11]:

$$\delta = \begin{cases} 2(\ln 10)x - \overline{C} & \text{if } x \ge x_1; \\ 2(\ln 10)x - \overline{C} + a(x_1 - x)^k & \text{if } x_0 \le x < x_1; \\ 0 & \text{if } x < x_0 \text{ (nonconductors);} \\ \delta_0 10^{2(x - x_0)} & \text{if } x < x_0 \text{ (conductors)} \end{cases} \tag{23.4}$$

Here $x = \log_{10}\eta = \log_{10}(p/Mc)$. $\overline{C}$ (the negative of the C used in Ref. 11) is obtained by equating the high-energy case of Eq. (23.4) with the limit given in Eq. (23.3). The other parameters are adjusted to give a best fit to the results of detailed calculations for momenta below $Mc\exp(x_1)$. Parameters for elements and nearly 200 compounds and mixtures of interest are published in a variety of places, notably in Ref. 14. A recipe for finding the coefficients for nontabulated materials given by Sternheimer and Peierls [13] is summarized in Ref. 10.

The remaining relativistic rise can be attributed to large energy transfers to a few electrons. If these escape or are otherwise accounted for separately, the energy deposited in an absorbing layer (in contrast to the energy lost by the particle) approaches a constant value, the Fermi plateau (see Sec. 23.2.5 below). The curve in Fig. 23.1 labeled "$T_{\rm cut} = 0.5$ MeV" illustrates this behavior. At extreme energies (*e.g.*, > 321 GeV for muons in iron), radiative effects are more important than ionization losses. These are especially relevant for high-energy muons, as discussed in Sec. 23.6.

23.2.2. ***Energy loss at low energies***: A shell correction C/Z is often included in the square brackets of Eq. (23.1) [3,5,7] to correct for atomic binding having been neglected in calculating some of the contributions to Eq. (23.1). We show the Barkas form [3] in Fig. 23.1. For copper it contributes about 1% at $\beta\gamma = 0.3$ (kinetic energy 6 MeV for a pion), and the correction decreases very rapidly with energy.

Eq. (23.1) is based on a first-order Born approximation. Higher-order corrections, again important only at lower energy, are normally included by adding a term $z^2 L_2(\beta)$ inside the square brackets.

An additional "Barkas correction" $z L_1(\beta)$ makes the stopping power for a negative particle somewhat larger than for a positive particle with the same mass and velocity. In a 1956 paper, Barkas *et al.* noted that negative pions had a longer range than positive pions [15]. The effect has been measured for a number of negative/positive particle pairs, most recently for antiprotons at the CERN LEAR facility [16].

A detailed discussion of low-energy corrections to the Bethe formula is given in ICRU Report 49 [5]. When the corrections are properly included, the accuracy of the Bethe-Bloch treatment is accurate to about 1% down to $\beta \approx 0.05$, or about 1 MeV for protons.

For $0.01 < \beta < 0.05$, there is no satisfactory theory. For protons, one usually relies on the empirical fitting formulae developed by Andersen and Ziegler [5,17]. For particles moving more slowly than $\approx 0.01c$ (more or less the velocity of the outer atomic electrons), Lindhard has been quite successful in describing electronic stopping power, which is proportional to β [18,19]. Finally, we note that at low energies, *e.g.*, for protons of less than several hundred eV, non-ionizing nuclear recoil energy loss dominates the total energy loss [5,19,20].

As shown in ICRU49 [5] (using data taken from Ref. 17), the nuclear plus electronic proton stopping power in copper is 113 MeV cm^2 g^{-1} at $T = 10$ keV, rises to a maximum of 210 MeV cm^2 g^{-1} at 100–150 keV, then falls to 120 MeV cm^2 g^{-1} at 1 MeV. Above 0.5–1.0 MeV the corrected Bethe-Block theory is adequate.

23.2.3. ***Fluctuations in energy loss***: The quantity $(dE/dx)\delta x$ is the mean energy loss via interaction with electrons in a layer of the medium with thickness δx. For finite δx, there are fluctuations in the actual energy loss. The distribution is skewed toward high values (the Landau tail) [1,21]. Only for a thick layer $[(dE/dx)\delta x \gg T_{\rm max}]$ is the distribution nearly Gaussian. The large fluctuations in the energy loss are due to the small number of collisions involving large energy transfers. The fluctuations are smaller for the so-called restricted energy loss rate, as discussed in Sec. 23.2.5 below.

23.2.4. ***Energy loss in mixtures and compounds***: A mixture or compound can be thought of as made up of thin layers of pure elements in the right proportion (Bragg additivity). In this case,

$$\frac{dE}{dx} = \sum w_j \left.\frac{dE}{dx}\right|_j , \tag{23.5}$$

where $dE/dx|_j$ is the mean rate of energy loss (in MeV g cm^{-2}) in the jth element. Eq. (23.1) can be inserted into Eq. (23.5) to find expressions for $\langle Z/A \rangle$, $\langle I \rangle$, and $\langle \delta \rangle$; for example, $\langle Z/A \rangle = \sum w_j Z_j/A_j = \sum n_j Z_j / \sum n_j A_j$. However, $\langle I \rangle$ as defined this way is an underestimate, because in a compound electrons are more tightly bound than in the free elements, and $\langle \delta \rangle$ as calculated this way has little relevance, because it is the electron density which matters. If possible, one uses the tables given in Refs. 14 and 10, which include effective excitation energies and interpolation coefficients for calculating the density effect correction for the chemical elements and nearly 200 mixtures and compounds. If a compound or mixture is not found, then one uses the recipe for δ given in Ref. 13 (or Ref. 22), and calculates $\langle I \rangle$ according to the discussion in Ref. 9. (Note the "13%" rule!)

23.2.5. ***Restricted energy loss rates for relativistic ionizing particles***: Fluctuations in energy loss are due mainly to the production of a few high-energy knock-on electrons. Practical detectors often measure the energy *deposited*, not the energy *lost*. When energy is carried off by energetic knock-on electrons, it is more appropriate to consider the mean energy loss excluding energy transfers greater than some cutoff $T_{\rm cut}$. The restricted energy loss rate is

$$\begin{aligned} -\left.\frac{dE}{dx}\right|_{T<T_{\rm cut}} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \Bigg[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\rm upper}}{I^2} \\ - \frac{\beta^2}{2} \left(1 + \frac{T_{\rm upper}}{T_{\rm max}} \right) - \frac{\delta}{2} \Bigg] \end{aligned} \tag{23.6}$$

where $T_{\rm upper} = {\rm MIN}(T_{\rm cut}, T_{\rm max})$. This form agrees with the equation given in previous editions of this *Review* [23] for $T_{\rm cut} \ll T_{\rm max}$ but smoothly joins the normal Bethe-Bloch function (Eq. (23.1)) for $T_{\rm cut} > T_{\rm max}$.

23.2.6. ***Energetic knock-on electrons (δ rays)***: The distribution of secondary electrons with kinetic energies $T \gg I$ is given by [1]

$$\frac{d^2N}{dT dx} = \frac{1}{2} K z^2 \frac{Z}{A} \frac{1}{\beta^2} \frac{F(T)}{T^2} \tag{23.7}$$

for $I \ll T \leq T_{\rm max}$, where $T_{\rm max}$ is given by Eq. (23.2). The factor F is spin-dependent, but is about unity for $T \ll T_{\rm max}$. For spin-0 particles $F(T) = (1 - \beta^2 T/T_{\rm max})$; forms for spins 1/2 and 1 are also given by Rossi [1]. When Eq. (23.7) is integrated from $T_{\rm cut}$ to $T_{\rm max}$,one obtains the difference between Eq. (23.1) and Eq. (23.6). For incident electrons, the indistinguishability of projectile and target means that the range of T extends only to half the kinetic energy of the incident particle. Additional formulae are given in Ref. 24. Equation (23.7) is inaccurate for T close to I: for $2I \lesssim T \lesssim 10I$, the $1/T^2$ dependence above becomes approximately $T^{-\eta}$, with $3 \lesssim \eta \lesssim 5$ [25].

23.2.7. ***Ionization yields***: Physicists frequently relate total energy loss to the number of ion pairs produced near the particle's track. This relation becomes complicated for relativistic particles due to the wandering of energetic knock-on electrons whose ranges exceed the dimensions of the fiducial volume. For a qualitative appraisal of the nonlocality of energy deposition in various media by such modestly energetic knock-on electrons, see Ref. 26. The mean local energy dissipation per local ion pair produced, W, while essentially constant for relativistic particles, increases at slow particle speeds [27]. For gases, W can be surprisingly sensitive to trace amounts of various contaminants [27]. Furthermore, ionization yields in practical cases may be greatly influenced by such factors as subsequent recombination [28].

23.3. Multiple scattering through small angles

A charged particle traversing a medium is deflected by many small-angle scatters. Most of this deflection is due to Coulomb scattering from nuclei, and hence the effect is called multiple Coulomb scattering. (However, for hadronic projectiles, the strong interactions also contribute to multiple scattering.) The Coulomb scattering distribution is well represented by the theory of Molière [29]. It is roughly Gaussian for small deflection angles, but at larger angles (greater than a few θ_0, defined below) it behaves like Rutherford scattering, having larger tails than does a Gaussian distribution.

If we define

$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}} \theta^{\rm rms}_{\rm space} . \tag{23.8}$$

then it is sufficient for many applications to use a Gaussian approximation for the central 98% of the projected angular distribution, with a width given by [30,31]

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} \Big[1 + 0.038 \ln(x/X_0) \Big] . \tag{23.9}$$

Here p, βc, and z are the momentum, velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths (defined below). This value of θ_0 is from a fit to Molière distribution [29] for singly charged particles with $\beta = 1$ for all Z, and is accurate to 11% or better for $10^{-3} < x/X_0 < 100$.

Eq. (23.9) describes scattering from a single material, while the usual problem involves the multiple scattering of a particle traversing many different layers and mixtures. Since it is from a fit to a Molière distribution, it is incorrect to add the individual θ_0 contributions in quadrature; the result is systematically too small. It is much more accurate to apply Eq. (23.9) once, after finding x and X_0 for the combined scatterer.

Lynch and Dahl have extended this phenomenological approach, fitting Gaussian distributions to a variable fraction of the Molière distribution for arbitrary scatterers [31], and achieve accuracies of 2% or better.

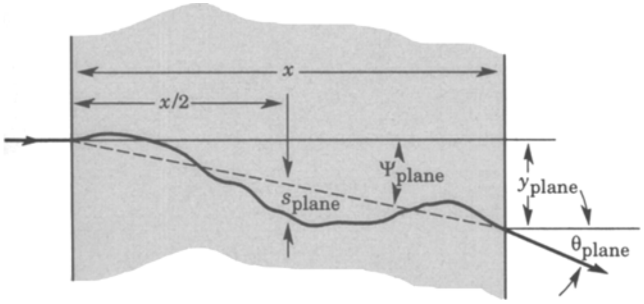

Figure 23.5: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

The nonprojected (space) and projected (plane) angular distributions are given approximately by [29]

$$\frac{1}{2\pi\,\theta_0^2}\exp\left\{-\frac{\theta_{\rm space}^2}{2\theta_0^2}\right\}d\Omega\ , \qquad (23.10)$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0}\exp\left\{-\frac{\theta_{\rm plane}^2}{2\theta_0^2}\right\}d\theta_{\rm plane}\ , \qquad (23.11)$$

where θ is the deflection angle. In this approximation, $\theta^2_{\rm space} \approx (\theta^2_{{\rm plane},x} + \theta^2_{{\rm plane},y})$, where the x and y axes are orthogonal to the direction of motion, and $d\Omega \approx d\theta_{{\rm plane},x}\, d\theta_{{\rm plane},y}$. Deflections into $\theta_{{\rm plane},x}$ and $\theta_{{\rm plane},y}$ are independent and identically distributed.

Figure 23.5 shows these and other quantities sometimes used to describe multiple Coulomb scattering. They are

$$\psi^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta_0\ , \qquad (23.12)$$

$$y^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta_0\ , \qquad (23.13)$$

$$s^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta_0\ . \qquad (23.14)$$

All the quantitative estimates in this section apply only in the limit of small $\theta^{\rm rms}_{\rm plane}$ and in the absence of large-angle scatters. The random variables s, ψ, y, and θ in a given plane are distributed in a correlated fashion (see Sec. 28.1 of this *Review* for the definition of the correlation coefficient). Obviously, $y \approx x\psi$. In addition, y and θ have the correlation coefficient $\rho_{y\theta} = \sqrt{3}/2 \approx 0.87$. For Monte Carlo generation of a joint $(y_{\rm plane}, \theta_{\rm plane})$ distribution, or for other calculations, it may be most convenient to work with independent Gaussian random-variables (z_1, z_2) with mean zero and variance one, and then set

$$\begin{aligned} y_{\rm plane} &= z_1\,x\,\theta_0(1-\rho^2_{y\theta})^{1/2}/\sqrt{3} + z_2\,\rho_{y\theta}x\,\theta_0/\sqrt{3} \\ &= z_1\,x\,\theta_0/\sqrt{12} + z_2\,x\,\theta_0/2\ ; \qquad (23.15) \\ \theta_{\rm plane} &= z_2\,\theta_0\ . \qquad (23.16) \end{aligned}$$

Note that the second term for $y_{\rm plane}$ equals $x\,\theta_{\rm plane}/2$ and represents the displacement that would have occurred had the deflection $\theta_{\rm plane}$ all occurred at the single point $x/2$.

For heavy ions the multiple Coulomb scattering has been measured and compared with various theoretical distributions [32].

23.4. Radiation length and associated quantities

In dealing with electrons and photons at high energies, it is convenient to measure the thickness of the material in units of the radiation length X_0. This is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and is the appropriate scale length for describing high-energy electromagnetic cascades. X_0 has been calculated and tabulated by Y.S. Tsai [33]:

$$\frac{1}{X_0} = 4\alpha r_e^2\frac{N_A}{A}\left\{Z^2\left[L_{\rm rad} - f(Z)\right] + Z\,L'_{\rm rad}\right\}\ . \qquad (23.17)$$

For $A = 1$ g mol^{-1}, $4\alpha r_e^2 N_A/A = (716.408\ {\rm g\ cm^{-2}})^{-1}$. $L_{\rm rad}$ and $L'_{\rm rad}$ are given in Table 23.2. The function $f(Z)$ is an infinite sum, but for elements up to uranium can be represented to 4-place accuracy by

$$\begin{aligned} f(Z) &= a^2\left[(1+a^2)^{-1} + 0.20206\right. \\ &\left. -0.0369\,a^2 + 0.0083\,a^4 - 0.002\,a^6\right]\ , \qquad (23.18) \end{aligned}$$

where $a = \alpha Z$ [34].

Table 23.2: Tsai's $L_{\rm rad}$ and $L'_{\rm rad}$, for use in calculating the radiation length in an element using Eq. (23.17).

Element	Z	$L_{\rm rad}$	$L'_{\rm rad}$
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	> 4	$\ln(184.15\,Z^{-1/3})$	$\ln(1194\,Z^{-2/3})$

Although it is easy to use Eq. (23.17) to calculate X_0, the functional dependence on Z is somewhat hidden. Dahl provides a compact fit to the data [35]:

$$X_0 = \frac{716.4\ {\rm g\ cm^{-2}}\ A}{Z(Z+1)\ln(287/\sqrt{Z})} \qquad (23.19)$$

Results obtained with this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the result is about 5% low.

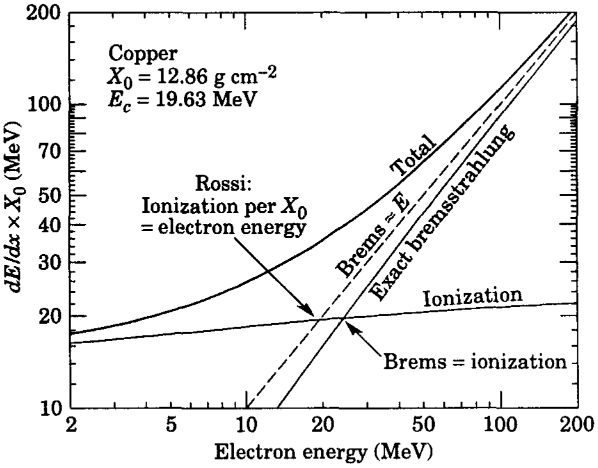

Figure 23.6: Two definitions of the critical energy E_c.

The radiation length in a mixture or compound may be approximated by

$$1/X_0 = \sum w_j/X_j\ , \qquad (23.20)$$

where w_j and X_j are the fraction by weight and the radiation length for the jth element.

An electron loses energy by bremsstrahlung at a rate nearly proportional to its energy, while the ionization loss rate varies only logarithmically with the electron energy. The *critical energy* E_c is sometimes defined as the energy at which the two loss rates are equal [36]. Berger and Seltzer [36] also give the approximation $E_c = (800\ {\rm MeV})/(Z+1.2)$. This formula has been widely quoted, and has been given in previous editions of this *Review* [23]. Among alternate definitions is that of Rossi [1], who defines the critical energy as the energy at which the ionization loss per radiation length is equal to the electron energy. Equivalently, it is the same as the first definition with the approximation $|dE/dx|_{\rm brems} \approx E/X_0$. These definitions are illustrated in the case of copper in Fig. 23.6.

The accuracy of approximate forms for E_c has been limited by the failure to distinguish between gases and solid or liquids, where there

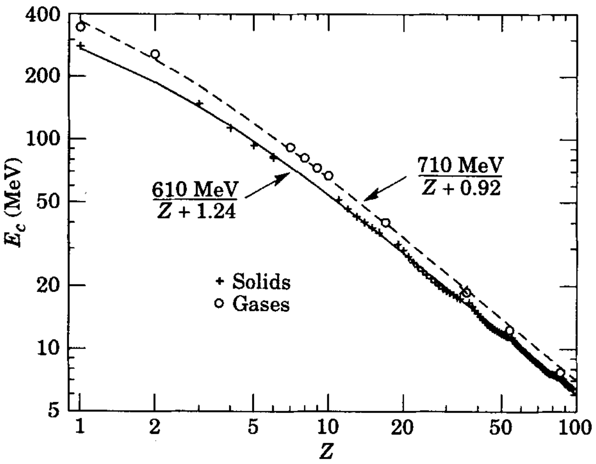

Figure 23.7: Electron critical energy for the chemical elements, using Rossi's definition [1]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassò.)

is a substantial difference in ionization at the relevant energy because of the density effect. We distinguish these two cases in Fig. 23.7. Fits were also made with functions of the form $a/(Z+b)^{\alpha}$, but α was essentially unity.

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by [37,38]

$$R_M = X_0\, E_s/E_c \ , \tag{23.21}$$

where $E_s \approx 21$ MeV (see Table 23.1), and the Rossi definition of E_c is used.

In a material containing a weight fraction w_j of the element with critical energy E_{cj} and radiation length X_j, the Molière radius is given by

$$\frac{1}{R_M} = \frac{1}{E_s}\sum \frac{w_j\, E_{cj}}{X_j} \ . \tag{23.22}$$

For very high-energy photons, the total e^+e^- pair-production cross section is approximately

$$\sigma = \tfrac{7}{9}(A/X_0 N_A) \ , \tag{23.23}$$

where A is the atomic weight of the material and N_A is Avogadro's number. Equation Eq. (23.23) is accurate to within a few percent down to energies as low as 1 GeV. The cross section decreases at lower energies, as shown in Fig. 24.4 of this *Review*. As the energy decreases, a number of other processes become important, as is shown in Fig. 24.3 of this *Review*.

23.5. Electromagnetic cascades

When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$\begin{aligned} t &= x/X_0 \\ y &= E/E_c \ , \end{aligned} \tag{23.24}$$

so that distance is measured in units of radiation length and energy in units of critical energy.

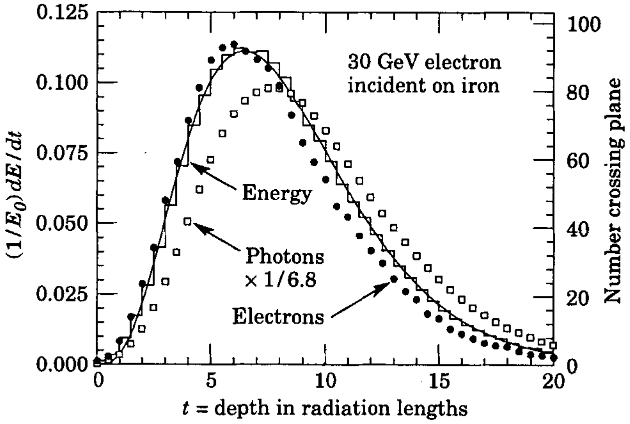

Figure 23.8: An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Longitudinal profiles for an EGS4 [22] simulation of a 30 GeV electron-induced cascade in iron are shown in Fig. 23.8. The number of particles crossing a plane (very close to Rossi's Π function [1]) is sensitive to the cutoff energy, here chosen as a total energy of 1.5 MeV for both electrons and photons. The electron number falls off more quickly than energy deposition. This is because, with increasing depth, a larger fraction of the cascade energy is carried by photons. Exactly what a calorimeter measures depends on the device, but it is not likely to be exactly any of the profiles shown. In gas counters it may be very close to the electron number, but in glass Čerenkov detectors and other devices with "thick" sensitive regions it is closer to the energy deposition (total track length). In such detectors the signal is proportional to the "detectable" track length T_d, which is in general less than the total track length T. Practical devices are sensitive to electrons with energy above some detection threshold E_d, and $T_d = T\,F(E_d/E_c)$. An analytic form for $F(E_d/E_c)$ obtained by Rossi [1] is given by Fabjan [39]; see also Amaldi [40].

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [41]:

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \tag{23.25}$$

The maximum $t_{\max}$ occurs at $(a-1)/b$. We have made fits to shower profiles in elements ranging from carbon to uranium, at energies from 1 GeV to 100 GeV. The energy deposition profiles are well described by Eq. (23.25) with

$$t_{\max} = (a-1)/b = 1.0 \times (\ln y + C_j) \ , \qquad j = e, \gamma \ , \tag{23.26}$$

where $C_e = -0.5$ for electron-induced cascades and $C_\gamma = +0.5$ for photon-induced cascades. To use Eq. (23.25), one finds $(a-1)/b$ from Eq. (23.26) and Eq. (23.24), then finds a either by assuming $b \approx 0.5$ or by finding a more accurate value from Fig. 23.9. The results are very similar for the electron number profiles, but there is some dependence on the atomic number of the medium. A similar form for the electron number maximum was obtained by Rossi in the context of his "Approximation B," [1] (see Fabjan's review in Ref. 39), but with $C_e = -1.0$ and $C_\gamma = -0.5$; we regard this as superseded by the EGS4 result.

The "shower length" $X_s = X_0/b$ is less conveniently parameterized, since b depends upon both Z and incident energy, as shown in Fig. 23.9. As a corollary of this Z dependence, the number of electrons crossing a plane near shower maximum is underestimated using Rossi's approximation for carbon and seriously overestimated for uranium. Essentially the same b values are obtained for incident electrons and photons. For many purposes it is sufficient to take $b \approx 0.5$.

The gamma distribution is very flat near the origin, while the EGS4 cascade (or a real cascade) increases more rapidly. As a result Eq. (23.25) fails badly for about the first two radiation lengths; it was necessary to exclude this region in making fits.

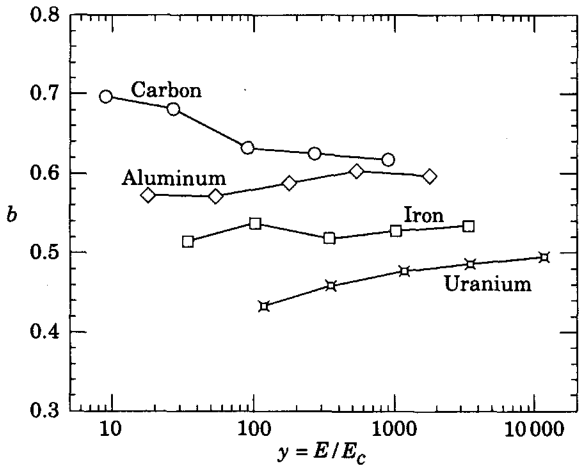

Figure 23.9: Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with $1 \leq E_0 \leq 100$ GeV. Values obtained for incident photons are essentially the same.

Because fluctuations are important, Eq. (23.25) should be used only in applications where average behavior is adequate. Grindhammer *et al.* have developed fast simulation algorithms in which the variance and correlation of a and b are obtained by fitting Eq. (23.25) to individually simulated cascades, then generating profiles for cascades using a and b chosen from the correlated distributions [42].

Measurements of the lateral distribution in electromagnetic cascades are shown in Refs. 37 and 38. On the average, only 10% of the energy lies outside the cylinder with radius R_M. About 99% is contained inside of $3.5R_M$, but at this radius and beyond composition effects become important and the scaling with R_M fails. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and Grindhammer [42] describes them with the function

$$f(r) = \frac{2r\,R^2}{(r^2+R^2)^2} \;, \qquad (23.27)$$

where R is a phenomenological function of x/X_0 and $\ln E$.

23.6. Muon energy loss at high energy

At sufficiently high energies, radiative processes become more important than ionization for all charged particles. For muons and pions in materials such as iron, this "critical energy" occurs at several hundred GeV. Radiative effects dominate the energy loss of energetic muons found in cosmic rays or produced at the newest accelerators. These processes are characterized by small cross sections, hard spectra, large energy fluctuations, and the associated generation of electromagnetic and (in the case of photonuclear interactions) hadronic showers [45–53]. As a consequence, at these energies the treatment of energy loss as a uniform and continuous process is for many purposes inadequate.

It is convenient to write the average rate of muon energy loss as [43]

$$-dE/dx = a(E) + b(E)\,E \;. \qquad (23.28)$$

Here $a(E)$ is the ionization energy loss given by Eq. (23.1), and $b(E)$ is the sum of e^+e^- pair production, bremsstrahlung, and photonuclear contributions. To the approximation that these slowly-varying functions are constant, the mean range x_0 of a muon with initial energy E_0 is given by

$$x_0 \approx (1/b)\ln(1 + E_0/E_{\mu c}) \;, \qquad (23.29)$$

where $E_{\mu c} = a/b$. Figure 23.10 shows contributions to $b(E)$ for iron. Since $a(E) \approx 0.002$ GeV g^{-1} cm^2, $b(E)E$ dominates the energy loss above several hundred GeV, where $b(E)$ is nearly constant. The rate of energy loss for muons in hydrogen, uranium, and iron is shown in Fig. 23.11 [44].

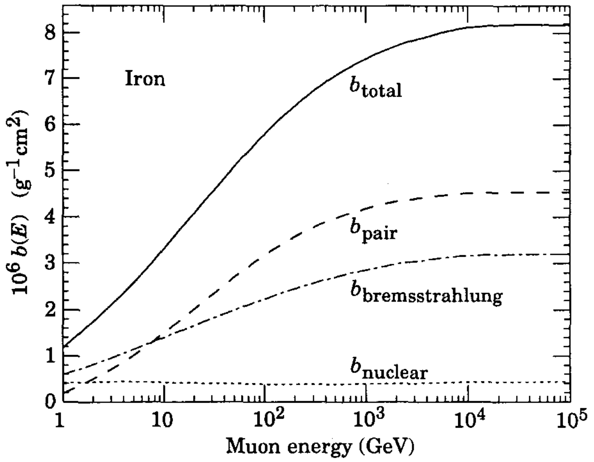

Figure 23.10: Contributions to the fractional energy loss by muons in iron due to e^+e^- pair production, bremsstrahlung, and photonuclear interactions, as obtained from Lohmann *et al.* [44].

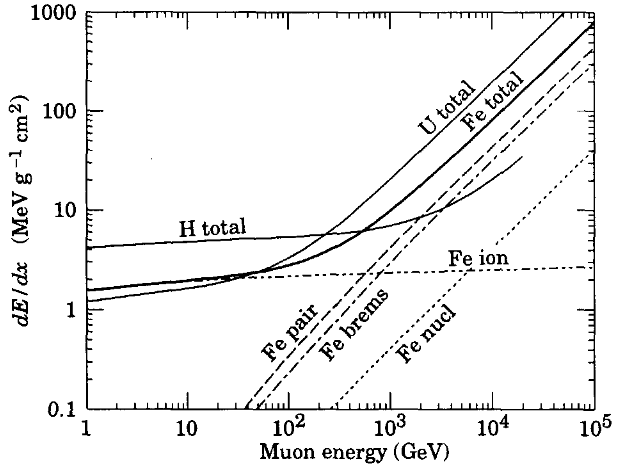

Figure 23.11: The average energy loss of a muon in hydrogen, iron, and uranium as a function of muon energy. Contributions to dE/dx in iron from ionization and the processes shown in Fig. 23.10 are also shown.

The "muon critical energy" $E_{\mu c}$ can be defined more exactly as the energy at which radiative and ionization losses are equal, and can be found by solving $E_{\mu c} = a(E_{\mu c})/b(E_{\mu c})$. This definition corresponds to the solid-line intersection in Fig. 23.6, and is different from the Rossi definition we used for electrons. It serves the same function: below $E_{\mu c}$ ionization losses dominate, and above $E_{\mu c}$ dominate. The dependence of $E_{\mu c}$ on atomic number Z is shown in Fig. 23.12.

The radiative cross sections are expressed as functions of the fractional energy loss ν. The bremsstrahlung cross section goes roughly as $1/\nu$ over most of the range, while for the pair production case the distribution goes as ν^{-3} to ν^{-2} (see Ref. 55). "Hard" losses are therefore more probable in bremsstrahlung, and in fact energy losses due to pair production may very nearly be treated as continuous. The calculated momentum distribution of an incident 1 TeV/c muon beam after it crosses 3 m of iron is shown in Fig. 23.13. The most probable loss is 9 GeV, or 3.8 MeV g^{-1}cm^2. The full width at half maximum is 7 GeV/c, or 0.7%. The radiative tail is almost entirely due to bremsstrahlung; this includes most of the 10% that lost more than 2.8% of their energy. Most of the 3.3% that lost more than 10% of their incident energy experienced photonuclear interactions, which are concentrated in rare, relatively hard collisions. The latter can exceed nominal detector resolution [56], necessitating the reconstruction of lost energy. Electromagnetic and hadronic cascades in detector materials can obscure muon tracks in detector planes and reduce tracking efficiency [57].

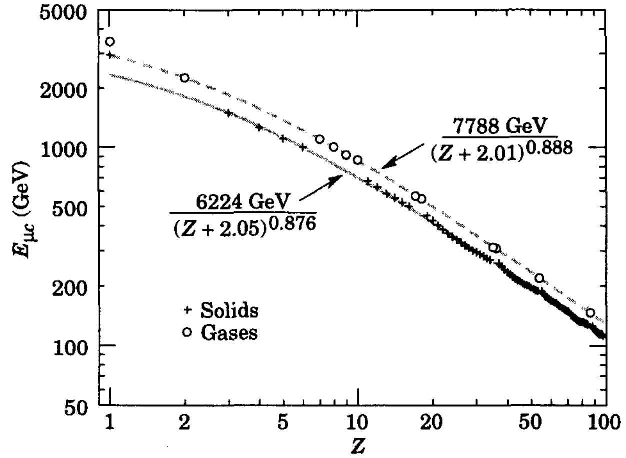

Figure 23.12: Muon critical energy for the chemical elements, defined as the energy at which radiative and ionization energy loss rates are equal. The equality comes at a higher energy for gases than for solids or liquids with the same atomic number because of a smaller density effect reduction of the ionization losses. The fits shown in the figure exclude hydrogen. Alkali metals fall 3–4% above the fitted function for alkali metals, while most other solids are within 2% of the function. Among the gases the worst fit is for neon (1.4% high). (Courtesy of N.V. Mokhov and S.I. Striganov.)

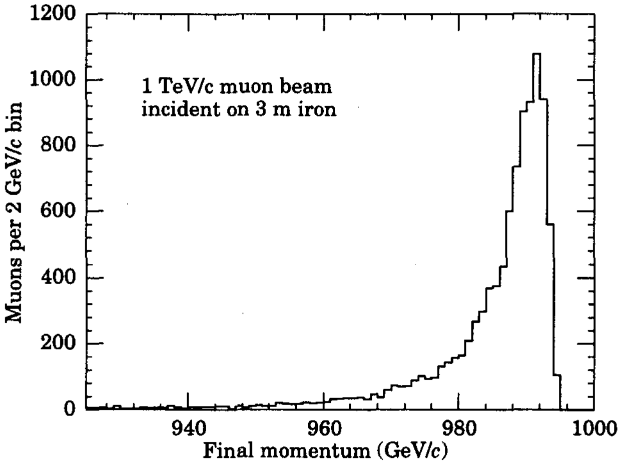

Figure 23.13: The momentum distribution of 1 TeV/c muons after traversing 3 m of iron, as obtained with Van Ginniken's TRAMU muon transport code [55].

23.7. Čerenkov and transition radiation [4,58,59]

A charged particle radiates if its velocity is greater than the local phase velocity of light (Čerenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation). Neither process is important for energy loss, but both are used in high-energy physics detectors.

Čerenkov Radiation. The half-angle θ_c of the Čerenkov cone for a particle with velocity βc in a medium with index of refraction n is

$$\begin{aligned}\theta_c &= \arccos(1/n\beta) \\ &\approx \sqrt{2(1-1/n\beta)} \quad \text{for small } \theta_c, \textit{e.g.} \text{ in gases.} \end{aligned} \tag{23.30}$$

The threshold velocity β_t is $1/n$, and $\gamma_t = 1/(1-\beta_t^2)^{1/2}$. Therefore, $\beta_t\gamma_t = 1/(2\delta+\delta^2)^{1/2}$, where $\delta = n - 1$. Values of δ for various commonly used gases are given as a function of pressure and wavelength in Ref. 60. For values at atmospheric pressure, see Table 6.1. Data for other commonly used materials are given in Ref. 61.

The number of photons produced per unit path length of a particle with charge ze and per unit energy interval of the photons is

$$\begin{aligned}\frac{d^2N}{dEdx} &= \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right) \\ &\approx 370\sin^2\theta_c(E)\ \text{eV}^{-1}\text{cm}^{-1} \qquad (z=1)\ , \end{aligned} \tag{23.31}$$

or, equivalently,

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) . \tag{23.32}$$

The index of refraction is a function of photon energy E, as is the sensitivity of the transducer used to detect the light. For practical use, Eq. (23.31) must be multiplied by the the transducer response function and integrated over the region for which $\beta\, n(E) > 1$. Further details are given in the discussion of Čerenkov detectors in the Detectors section (Sec. 25 of this *Review*).

Transition Radiation. The energy radiated when a particle with charge ze crosses the boundary between vacuum and a medium with plasma frequency ω_p is

$$I = \alpha z^2 \gamma \hbar\omega_p/3\ , \tag{23.33}$$

where

$$\begin{aligned}\hbar\omega_p &= \sqrt{4\pi N_e r_e^3}\ m_e c^2/\alpha \\ &= \sqrt{4\pi N_e a_\infty^3}\ 2\times 13.6\ \text{eV}\ . \end{aligned} \tag{23.34}$$

Here N_e is the electron density in the medium, r_e is the classical electron radius, and a_∞ is the Bohr radius. For styrene and similar materials, $\sqrt{4\pi N_e a_\infty^3} \approx 0.8$, so that $\hbar\omega_p \approx 20$ eV. The typical emission angle is $1/\gamma$.

The radiation spectrum is logarithmically divergent at low energies and decreases rapidly for $\hbar\omega/\gamma\hbar\omega_p > 1$. About half the energy is emitted in the range $0.1 \le \hbar\omega/\gamma\hbar\omega_p \le 1$. For a particle with $\gamma = 10^3$, the radiated photons are in the soft x-ray range 2 to 20 eV. The γ dependence of the emitted energy thus comes from the hardening of the spectrum rather than from an increased quantum yield. For a typical radiated photon energy of $\gamma\hbar\omega_p/4$, the quantum yield is

$$\begin{aligned}N_\gamma &\approx \frac{1}{2}\,\frac{\alpha z^2\gamma\hbar\omega_p}{3}\Big/\frac{\gamma\hbar\omega_p}{4} \\ &\approx \tfrac{2}{3}\alpha z^2 \approx 0.5\% \times z^2\ . \end{aligned} \tag{23.35}$$

More precisely, the number of photons with energy $\hbar\omega > \hbar\omega_0$ is given by [4]

$$N_\gamma(\hbar\omega > \hbar\omega_0) = \frac{\alpha z^2}{\pi}\left[\left(\ln\frac{\gamma\hbar\omega_p}{\hbar\omega_0} - 1\right)^2 + \frac{\pi^2}{12}\right]\ , \tag{23.36}$$

within corrections of order $(\hbar\omega_0/\gamma\hbar\omega_p)^2$. The number of photons above a fixed energy $\hbar\omega_0 \ll \gamma\hbar\omega_p$ thus grows as $(\ln\gamma)^2$, but the number above a fixed fraction of $\gamma\hbar\omega_p$ (as in the example above) is constant. For example, for $\hbar\omega > \gamma\hbar\omega_p/10$, $N_\gamma = 2.519\,\alpha z^2/\pi = 0.59\% \times z^2$.

The yield can be increased by using a stack of plastic foils with gaps between. However, interference can be important, and the soft x rays are readily absorbed in the foils. The first problem can be overcome by choosing thicknesses and spacings large compared to the "formation length" $D = \gamma c/\omega_p$, which in practical situations is tens of μm. Other practical problems are discussed in Sec. 25.

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24. PHOTON AND ELECTRON INTERACTIONS WITH MATTER

Revised April 1998 by D.E. Groom (LBNL).

Photon Attenuation Length

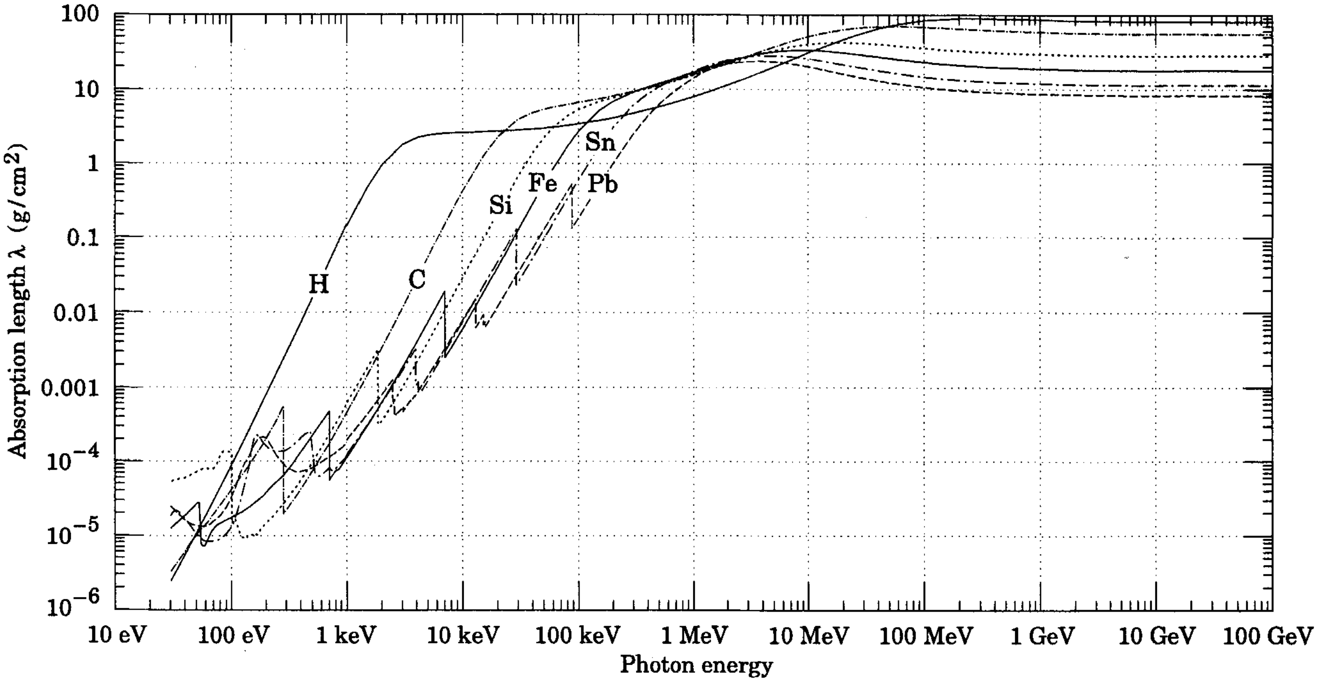

Figure 24.1: The photon mass attenuation length (or mean free path) $\lambda = 1/(\mu/\rho)$ for various elemental absorbers as a function of photon energy. The mass attenuation coefficient is μ/ρ, where ρ is the density. The intensity I remaining after traversal of thickness t (in mass/unit area) is given by $I = I_0 \exp(-t/\lambda)$. The accuracy is a few percent. For a chemical compound or mixture, $1/\lambda_{\rm eff} \approx \sum_{\rm elements} w_Z/\lambda_Z$, where w_Z is the proportion by weight of the element with atomic number Z. The processes responsible for attenuation are given in Fig. 24.4. Since coherent processes are included, not all these processes result in energy deposition.

The data for 30 eV $< E <$ 1 keV are obtained from `http://www-cxro.lbl.gov/optical_constants` (courtesy of Eric M. Gullikson, LBNL). The data for 1 keV $< E <$ 100 GeV are from `http://physics.nist.gov/PhysRefData`, through the courtesy of John H. Hubbell (NIST).

Photon Pair Conversion Probability

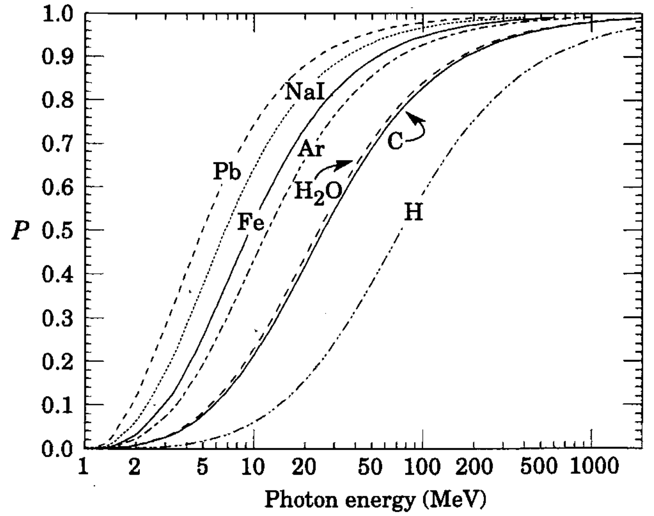

Figure 24.2: Probability P that a photon interaction will result in conversion to an e^+e^- pair. Except for a few-percent contribution from photonuclear absorption around 10 or 20 MeV, essentially all other interactions in this energy range result in Compton scattering off an atomic electron. For a photon attenuation length λ (Fig. 24.1), the probability that a given photon will produce an electron pair (without first Compton scattering) in thickness t of absorber is $P[1 - \exp(-t/\lambda)]$.

Contributions to Photon Cross Section in Carbon and Lead

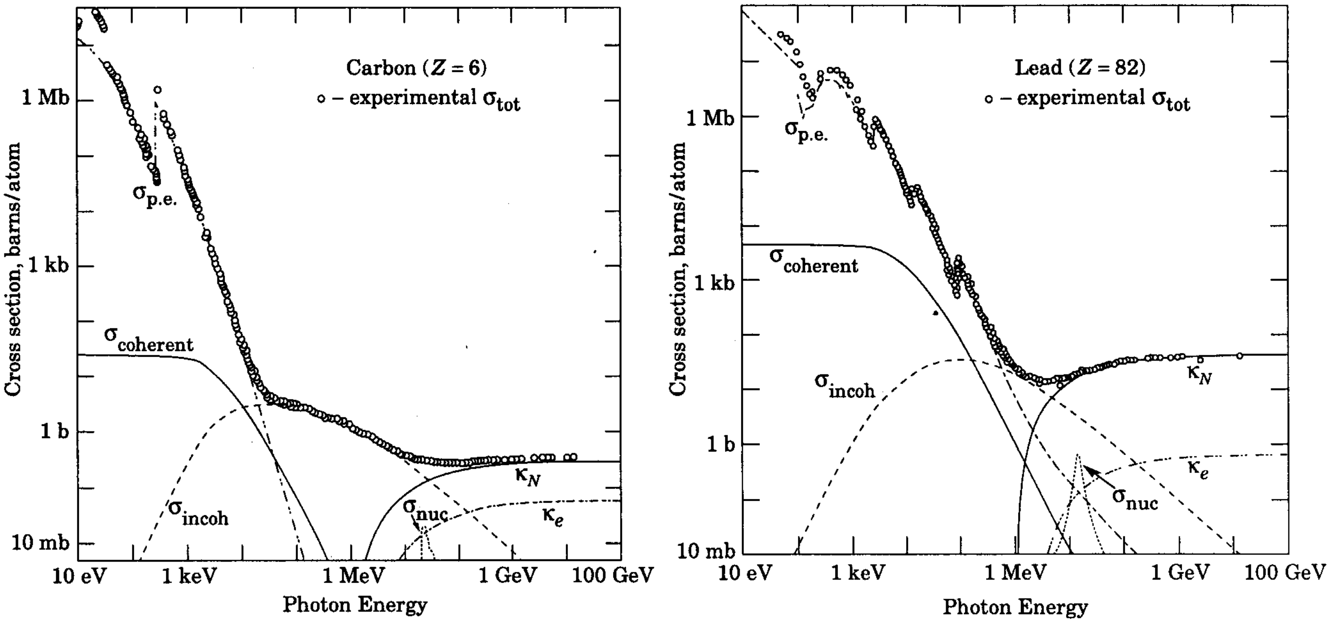

Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

$\sigma_{\text{p.e.}}$ = Atomic photo-effect (electron ejection, photon absorption)
σ_{coherent} = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
$\sigma_{\text{incoherent}}$ = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from `http://physics.nist.gov/PhysRefData`. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell (NIST).

Fractional Energy Loss for Electrons and Positrons in Lead

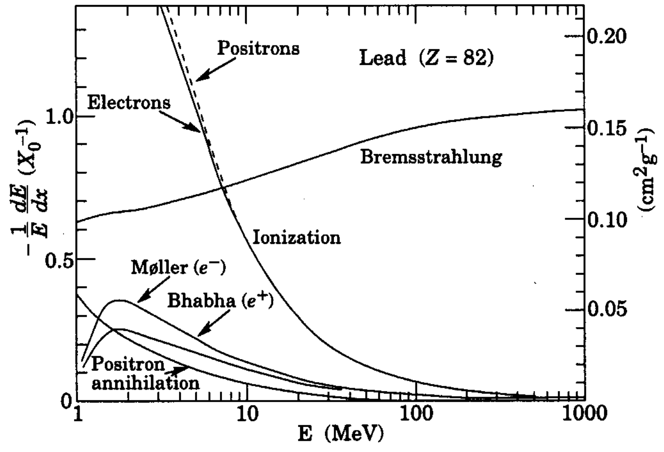

Figure 24.4: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Moller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\text{Pb}) = 5.82\ \text{g/cm}^2$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials, namely $X_0(\text{Pb}) = 6.4\ \text{g/cm}^2$. The development of electron-photon cascades is approximately independent of absorber when the results are expressed in terms of inverse radiation lengths (*i.e.*, scale on left of plot).

25. PARTICLE DETECTORS

Revised 1997 (see the various sections for authors).

In this section we give various parameters for common detector components. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. A more detailed discussion of detectors can be found in Ref. 1. In Table 25.1 are given typical spatial and temporal resolutions of common detectors.

Table 25.1: Typical detector characteristics.

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq$ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	$\frac{\text{pitch}^{e}}{3\text{ to }7}$	[f]	[f]
Silicon pixel	2 μm[g]	[f]	[f]

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give ± 150 μm parallel to anode wire.

[d] For two chambers.

[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim 25$ μm) with pulse-height-weighted center finding.

[f] Limited at present by properties of the readout electronics. (Time resolution of ≤ 15 ns is planned for the SDC silicon tracker.)

[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

25.1. Organic scintillators

Written October 1995 by K.F. Johnson (FSU).

Organic scintillators are broadly classed into three types, crystalline, liquid, and plastic, all of which utilize the ionization produced by charged particles (see the section on "Passage of particles through matter" (Sec. 23.2) of this *Review*) to generate optical photons, usually in the blue to green wavelength regions [2]. Plastic scintillators are by far the most widely used and we address them primarily; however, most of the discussion will also have validity for liquid scintillators with obvious caveats. Crystal organic scintillators are practically unused in high-energy physics.

Densities range from 1.03 to 1.20 g cm^{-3}. Typical photon yields are about 1 photon per 100 eV of energy deposit [3]. A one-cm-thick scintillator traversed by a minimum-ionizing particle will therefore yield $\approx 2 \times 10^4$ photons. The resulting photoelectron signal will depend on the collection and transport efficiency of the optical package and the quantum efficiency of the photodetector.

Plastic scintillators do not respond linearly to the ionization density. Very dense ionization columns emit less light than expected on the basis of dE/dx for minimum-ionizing particles. A widely used semi-empirical model by Birks posits that recombination and quenching effects between the excited molecules reduce the light yield [9]. These effects are more pronounced the greater the density of the excited molecules. Birks' formula is

$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B\, dE/dx} , \tag{25.1}$$

where $\mathscr{L}$ is the luminescence, $\mathscr{L}_0$ is the luminescence at low specific ionization density, and k_B is Birks' constant, which must be determined for each scintillator by measurement.

Decay times are in the ns range; risetimes are much faster. The combination of high light yield and fast response time allows the possibility of sub-ns timing resolution [4]. The fraction of light emitted during the decay "tail" can depend on the exciting particle. This allows pulse shape discrimination as a technique to carry out particle identification. Because of the hydrogen content (carbon to hydrogen ratio ≈ 1) plastic scintillator is sensitive to proton recoils from neutrons. Ease of fabrication into desired shapes and low cost has made plastic scintillators a common detector component. Recently, plastic scintillators in the form of scintillating fibers have found widespread use in tracking and calorimetry [5].

25.1.1. *Scintillation mechanism* :

Scintillation: A charged particle traversing matter leaves behind it a wake of excited molecules. Certain types of molecules, however, will release a small fraction ($\approx 3\%$) of this energy as optical photons. This process, scintillation, is especially marked in those organic substances which contain aromatic rings, such as polystyrene, polyvinyltoluene, and napthalene. Liquids which scintillate include toluene and xylene.

Fluorescence: In fluorescence, the initial excitation takes place via the absorption of a photon, and de-excitation by emission of a longer wavelength photon. Fluors are used as "waveshifters" to shift scintillation light to a more convenient wavelength. Occurring in complex molecules, the absorption and emission are spread out over a wide band of photon energies, and have some overlap, that is, there is some fraction of the emitted light which can be re-absorbed [6]. This "self-absorption" is undesirable for detector applications because it causes a shortened attenuation length. The wavelength difference between the major absorption and emission peaks is called the Stokes' shift. It is usually the case that the greater the Stokes' shift, the smaller the self absorption—thus, a large Stokes' shift is a desirable property for a fluor.

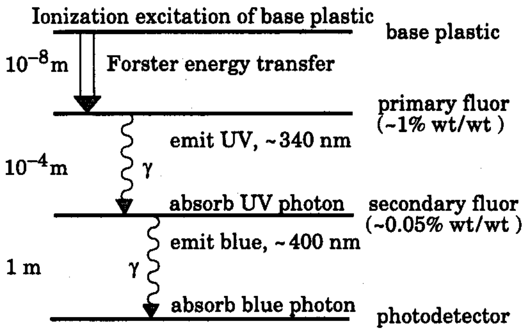

Figure 25.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

Scintillators: The plastic scintillators used in high-energy physics are binary or ternary solutions of selected fluors in a plastic base containing aromatic rings. (See the appendix in Ref. 7 for a comprehensive list of plastic scintillator components.) Virtually all plastic scintillators contain as a base either polyvinyltoluene, polystyrene, or acrylic, whereby polyvinyltoluene-based scintillator can be up to 50% brighter than the others. Acrylic is non-aromatic and has therefore a very low scintillation efficiency. It becomes an acceptable scintillator when napthalene, a highly aromatic compound, is dissolved into the acrylic at 5% to 20% weight fraction. Thus, in "acrylic" scintillator the active component is napthalene. The fluors must satisfy additional conditions besides being fluorescent. They must be sufficiently stable, soluble, chemically inert, fast, radiation tolerant, and efficient.

The plastic base is the ionization-sensitive (*i.e.*, the scintillator) portion of the plastic scintillator (see Fig. 25.1). In the absence of fluors the base would emit UV photons with short attenuation length (several mm). Longer attenuation lengths are obtained by dissolving a "primary" fluor in high concentration (1% by weight) into the base, which is selected to efficiently reradiate absorbed energy at wavelengths where the base is more transparent.

The primary fluor has a second important function. The decay time of the scintillator base material can be quite long—in pure polystyrene it is 16 ns, for example. The addition of the primary fluor in high concentration can shorten the decay time by an order of magnitude and increase the total light yield. At the concentrations used (1% and greater), the average distance between a fluor molecule and an excited base unit is around 100 Å, much less than a wavelength of light. At these distances the predominant mode of energy transfer from base to fluor is not the radiation of a photon, but a resonant dipole-dipole interaction, first described by Foerster, which strongly couples the base and fluor [8]. The strong coupling sharply increases the speed and the light yield of the plastic scintillators.

Unfortunately, a fluor which fulfills other requirements is usually not completely adequate with respect to emission wavelength or attenuation length, so it is necessary to add yet another waveshifter (the "secondary" fluor), at fractional percent levels, and ocassionally a third (not shown in Fig. 25.1).

External wavelength shifters: Light emitted from a plastic scintillator may be absorbed in a (nonscintillating) base doped with a waveshifting fluor. Such wavelength shifters are widely used to aid light collection in complex geometries. The wavelength shifter must be insensitive to ionizing radiation and Čerenkov light. A typical wavelength shifter uses an acrylic base (without napthalene!) because of its good optical qualities, a single fluor to shift the light emerging from the plastic scintillator to the blue-green, and contains ultra-violet absorbing additives to deaden response to Čerenkov light.

25.1.2. ***Caveats and cautions***: Plastic scintillators are reliable, robust, and convenient. However, they possess quirks to which the experimenter must be alert.

Aging and Handling: Plastic scintillators are subject to aging which diminishes the light yield. Exposure to solvent vapors, high temperatures, mechanical flexing, irradiation, or rough handling will aggravate the process. A particularly fragile region is the surface which can "craze"—develop microcracks—which rapidly destroy the capability of plastic scintillators to transmit light by total internal reflection. Crazing is particularly likely where oils, solvents, or *fingerprints* have contacted the surface.

Attenuation length: The Stokes' shift is not the only factor determining attenuation length. Others are the concentration of fluors (the higher the concentration of a fluor, the greater will be its self-absorption); the optical clarity and uniformity of the bulk material; the quality of the surface; and absorption by additives, such as stabilizers, which may be present.

Afterglow: Plastic scintillators have a long-lived luminescence which does not follow a simple exponential decay. Intensities at the 10^{-4} level of the initial fluorescence can persist for hundreds of ns [10].

Atmospheric quenching: Plastic scintillators will decrease their light yield with increasing partial pressure of oxygen. This can be a 10% effect in an artificial atmosphere [11]. It is not excluded that other gasses may have similar quenching effects.

Magnetic field: The light yield of plastic scintillators may be changed by a magnetic field. The effect is very nonlinear and apparently not all types of plastic scintillators are so affected. Increases of ≈ 3% at 0.45 T have been reported [12]. Data are sketchy and mechanisms are not understood.

Radiation damage: Irradiation of plastic scintillators creates color centers which absorb light more strongly in the UV and blue than at longer wavelengths. This poorly understood effect appears as a reduction both of light yield and attenuation length. Radiation damage depends not only on the integrated dose, but on the dose rate, atmosphere, and temperature, before, during and after irradiation, as well as the materials properties of the base such as glass transition temperature, polymer chain length, *etc.* Annealing also occurs, accelerated by the diffusion of atmospheric oxygen and elevated temperatures. The phenomena are complex, unpredictable, and not well understood [13]. Since color centers are less intrusive at longer wavelengths, the most reliable method of mitigating radiation damage is to shift emissions at every step to the longest practical wavelengths, *e.g.*, utilize fluors with large Stokes' shifts.

25.2. Inorganic scintillators

Written October 1995 by C.L. Woody (BNL).

Table 25.2 gives a partial list of commonly-used inorganic scintillators in high-energy and nuclear physics [14–21]. These scintillating crystals are generally used where high density and good energy resolution are required. In a crystal which contains nearly all of the energy deposited by an incident particle, the energy resolution is determined largely, but not totally, by the light output. The table gives the light output of the various materials relative to NaI, which has an intrinsic light output of about 40000 photons per MeV of energy deposit. The detected signal is usually quoted in terms of photoelectrons per MeV produced by a given photodetector. The relationship between photons/MeV produced and p.e.'s/MeV detected involves factors for light collection efficiency (typically 10–50%, depending on geometry) and the quantum efficiency of the detector (~ 15–20% for photomultiplier tubes and ~ 70% for silicon photodiodes for visible wavelengths). The quantum efficiency of the detector is usually highly wavelength dependent and should be matched to the particular crystal of interest to give the highest quantum yield at the wavelength corresponding to the peak of the scintillation emission. The comparison of the light output given in Table 25.2 is for a standard photomultiplier tube with a bialkali photocathode. Results with photodiodes can be significantly different; *e.g.*, the CsI(Tl) response relative to NaI(Tl) is 1.4 rather than 0.40 [21]. For scintillators which emit in the UV, a detector with a quartz window should be used.

25.3. Čerenkov detectors

Written October 1993 by D.G. Coyne (UCSC).

Čerenkov detectors utilize one or more of the properties of Čerenkov radiation discussed in the Passages of Particles through Matter section (Sec. 23 of this *Review*): the existence of a ***threshold*** for radiation; the dependence of the Čerenkov cone half-angle θ_c on the ***velocity*** of the particle; the dependence of the ***number of emitted photons*** on the particle's velocity. The presence of the refractive index n in the relations allows tuning these quantities for a particular experimental application (*e.g.*, using pressurized gas and/or various liquids as radiators).

The number of photoelectrons (p.e.'s) detected in a given device or channel is

$$N_{\rm p.e.} = L\frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}(E)\,\epsilon_{\rm det}(E)\sin^2\theta_c(E)dE \ , \qquad (25.2)$$

where L is the path length in the radiator, $\epsilon_{\rm coll}$ is the efficiency for collecting the Čerenkov light, $\epsilon_{\rm det}$ is the quantum efficiency of the transducer (photomultiplier or equivalent), and $\alpha^2/(r_e\, m_e c^2) =$ 370 $\text{cm}^{-1}\text{eV}^{-1}$. The quantities $\epsilon_{\rm coll}$, $\epsilon_{\rm det}$, and θ_c are all functions of the photon energy E, although in typical detectors θ_c (or, equivalently, the index of refraction) is nearly constant over the useful range of photocathode sensitivity. In this case,

$$N_{\rm p.e.} \approx LN_0 \left\langle \sin^2\theta_c \right\rangle \qquad (25.3)$$

with

$$N_0 = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}\,\epsilon_{\rm det} dE \ . \qquad (25.4)$$

We take $z = 1$, the usual case in high-energy physics, in the following discussion.

Threshold Čerenkov detectors make a simple yes/no decision based on whether the particle is above/below the Čerenkov threshold velocity

Table 25.2: Properties of several inorganic crystal scintillators.

NaI(Tl)	BGO	BaF_2	CsI(Tl)	CsI(pure)	$PbWO_4$	CeF_3
Density ($g\ cm^{-3}$):						
3.67	7.13	4.89	4.53	4.53	8.28	6.16
Radiation length (cm):						
2.59	1.12	2.05	1.85	1.85	0.89	1.68
Molière radius (cm):						
4.5	2.4	3.4	3.8	3.8	2.2	2.6
***dE/dx* (MeV/cm) (per mip):**						
4.8	9.2	6.6	5.6	5.6	13.0	7.9
Nucl. int. length (cm):						
41.4	22.0	29.9	36.5	36.5	22.4	25.9
Decay time (ns):						
250	300	0.7^f 620^s	1000	$10, 36^f$ $\sim 1000^s$	5–15	10–30
Peak emission λ (nm):						
410	480	220^f 310^s	565	305^f $\sim 480^s$	440–500	310–340
Refractive index:						
1.85	2.20	1.56	1.80	1.80	2.16	1.68
Relative light output:*						
1.00	0.15	0.05^f 0.20^s	0.40	0.10^f 0.02^s	0.01	0.10
Hygroscopic:						
very	no	slightly	somewhat	somewhat	no	no

* For standard photomultiplier tube with a bialkali photocathode. See Ref. 21 for photodiode results.

f = fast component, s = slow component

$\beta_t = 1/n$. Careful designs give $\langle\epsilon_{\rm coll}\rangle \gtrsim 90\%$. For a photomultiplier with a typical bialkali cathode, $\int \epsilon_{\rm det} dE \approx 0.27$, so that

$$N_{\rm p.e.}/L \approx 90\ {\rm cm}^{-1} \left\langle \sin^2\theta_c \right\rangle \qquad (i.e.,\ N_0 = 90\ {\rm cm}^{-1})\ . \tag{25.5}$$

Suppose, for example, that n is chosen so that the threshold for species a is p_t; that is, at this momentum species a has velocity $\beta_a = 1/n$. A second, lighter, species b with the same momentum has velocity β_b, so $\cos\theta_c = \beta_a/\beta_b$, and

$$\frac{N_{\rm p.e.}}{L} \approx 90\ {\rm cm}^{-1}\, \frac{m_a^2 - m_b^2}{p_t^2 + m_a^2}\ . \tag{25.6}$$

For K/π separation at $p = 1$ GeV/c, $N_{\rm p.e.}/L \approx 16\ {\rm cm}^{-1}$ for π's and (by design) 0 for K's.

For limited path lengths $N_{\rm p.e.}$ can be small, and some minimum number is required to trigger external electronics. The overall efficiency of the device is controlled by Poisson fluctuations, which can be especially critical for separation of species where one particle type is dominant [22].

A related class of detectors uses the number of observed photoelectrons (or the calibrated pulse height) to discriminate between species or to set probabilities for each particle species [23].

Differential Čerenkov detectors exploit the dependence of θ_c on β, using optical focusing and/or geometrical masking to select particles having velocities in a specified region. With careful design, a velocity resolution of $\sigma_\beta/\beta \approx 10^{-4}$–$10^{-5}$ can be obtained [22,24].

Ring-Imaging Čerenkov detectors use all three properties of Čerenkov radiation in both small-aperture and 4π geometries. They are principally used as hypothesis-testing rather than yes/no devices; that is, the probability of various identification possibilities is established from θ_c and $N_{\rm p.e.}$ for a particle of known momentum. In most cases the optics map the Čerenkov cone onto a circle at the photodetector, often with distortions which must be understood.

The 4π devices [25,26] typically have both liquid (C_6F_{14}, $n = 1.276$) and gas (C_5F_{12}, $n = 1.0017$) radiators, the light from the latter being focused by mirrors. They achieve 3 σ separation of $e/\pi/K/p$ over wide ranges, as shown in Table 25.3. Great attention to detail, especially with the minimization of UV-absorbing impurities, is required to get $\langle\epsilon_{\rm coll}\rangle \gtrsim 50\%$.

Table 25.3: Momentum range for 3σ separation in the SLD ring-imaging Čerenkov detector.

Particle pair	Mom. range for 3 σ separation
e/π	$p \lesssim 5$ GeV/c
π/K	$0.23 \lesssim p \lesssim 20$ GeV/c
K/p	$0.82 \lesssim p \lesssim 30$ GeV/c

The phototransducer is typically a TPC/wire-chamber combination sensitive to single photoelectrons and having charge division or pads. This construction permits three-dimensional reconstruction of photoelectron origins, which is important for transforming the Čerenkov cone into a ring. Single photoelectrons are generated by doping the TPC gas (for instance, ethane/methane in some proportion) with $\sim 0.05\%$ TMAE [tetrakis(dimethylamino)ethylene] [27], leading to photon absorption lengths along the Čerenkov cone of ~ 30 mm. The readout wires must be equipped with special structures (blinds or wire gates) to prevent photon feedback from avalanches generating cross-talk photoelectrons in the TPC. Drift-gas purity must be maintained to assure mean drift lengths of the order of meters without recombination (*i.e.*, lifetimes of $\gtrsim 100\ \mu$s at typical drift velocities of $\gtrsim 4$ cm/μs). The net $\langle\epsilon_{\rm det}\rangle$'s reach 30%, with the limitation being the TMAE quantum efficiency.

Photon energy cutoffs are set by the TMAE ($E > 5.4$ eV), the UV transparency of fused silica glass ($E < 7.4$ eV), and the C_6F_{14} ($E < 7.1$ eV). With effort one gets $50 \leq N_0 \leq 100$ for complete rings using liquid or gas. This includes losses due to electrostatic shielding wires and window/mirror reflections, but not gross losses caused by total internal reflection or inadequate coverage by the TPC's.

Such numbers allow determination of ring radii to $\sim$0.5% (liquid) and $\sim$2% (gas), leading to the particle species separations quoted above. Since the separation efficiencies may have "holes" as a function of p, detailed calculations are necessary.

25.4. Transition radiation detectors (TRD's)

Revised February 1998 by D. Froidevaux (CERN).

It is clear from the discussion in the Passages of Particles Through Matter section (Sec. 23 of this *Review*) that transition radiation (TR) only becomes useful for particle detectors when the signal can be observed as x rays emitted along the particle direction for Lorentz factors γ larger than 1000. In practice, TRD's are therefore used to provide electron/pion separation for 0.5 GeV/$c \lesssim p \lesssim 100$ GeV/c. The charged-particle momenta have usually been measured elsewhere in the detector in the past [28].

Since soft x rays, in the useful energy range between 2 and 20 keV, are radiated with about 1% probability per boundary crossing, practical detectors use radiators with several hundred interfaces, *e.g.* foils or fibres of low-Z materials such as polypropylene (or, more rarely, lithium) in a gas. Absorption inside the radiator itself and in the inactive material of the x-ray detector is important and limits the usefulness of the softer x rays, but interference effects are even larger, and saturate the x-ray yield for electron energies above a few GeV [29,30].

A classical detector is composed of several similar modules, each consisting of a radiator and an x-ray detector, which is usually a wire chamber operated with a xenon-rich mixture, in order efficiently to absorb the x rays. Since transition-radiation photons are mostly emitted at very small angles with respect to the charged-particle direction, the x-ray detector most often detects the sum of the ionization loss (dE/dx) of the charged particle in the gas and energy deposition of the x rays. The discrimination between electrons and pions can be based on the charges measured in each detection module, on the number of energy clusters observed above an optimal threshold (usually in the 5 to 7 keV region), or on more sophisticated methods analysing the pulse shape as a function of time. Once properly calibrated and optimized, most of these methods yield very similar results.

More recent development work has aimed at increasing the intrinsic quality of the TRD-performance by increasing the probability per detection module of observing a signal from TR-photons produced by electrons. This has been achieved experimentally by distributing small-diameter straw-tube detectors uniformly throughout the radiator material [31]. This method has thereby also cured one of the major drawbacks of more classical TRD's, that is, their need to rely on another detector to measure the charged-particle trajectory. For example, in the straw tracker proposed for one of the LHC experiments [32], charged particles cross about 40 straw tubes embedded in the radiator material. Dedicated R&D work and detailed simulations have shown that the combination of charged-track measurement and particle identification in the same detector will provide a very powerful tool even at the highest LHC luminosity.

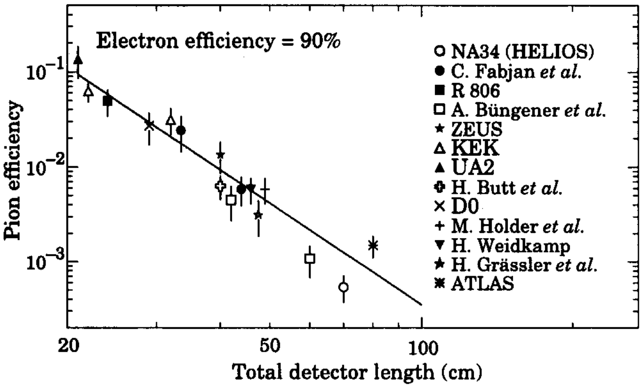

Figure 25.2: Pion efficiency measured (or predicted) for different TRDs as a function of the detector length for a fixed electron efficiency of 90%. The experimental data are directly taken or extrapolated from references [33–45] (top to bottom).

The major factor in the performance of any TRD is its overall length. This is illustrated in Fig. 25.2, which shows, for a variety of detectors, the measured (or predicted) pion efficiency at a fixed electron efficiency of 90% as a function of the overall detector length. The experimental data cover too wide a range of particle energies (from a few GeV to 40 GeV) to allow for a quantitative fit to a universal curve. Fig. 25.2 shows that an order of magnitude in rejection power against pions is gained each time the detector length is increased by ~ 20 cm.

25.5. Silicon photodiodes and particle detectors

Written October 1993 by H.F.W. Sadrozinski (UCSC) and H.G. Spieler (LBNL).

Silicon detectors are *p-n* junction diodes operated at reverse bias. This forms a sensitive region depleted of mobile charge and sets up an electric field that sweeps charge liberated by radiation to the electrodes. The thickness of the depleted region is

$$W = \sqrt{\frac{2\epsilon(V + V_{bi})}{ne}} = \sqrt{2\rho\mu\epsilon(V + V_{bi})} \; , \qquad (25.7)$$

where $V =$ external bias voltage

$V_{bi} =$ "built-in" voltage (≈ 0.8 V for resistivities typically used in detectors

$n =$ doping concentration

$e =$ electron charge

$\epsilon =$ dielectric constant $= 11.9\,\epsilon_0 \approx 1$ pF/cm

$\rho =$ resistivity (typically 1–10 kΩ cm)

$\mu =$ charge carrier mobility

$= 1350$ cm^2 V^{-1} s^{-1} for electrons (n-type material)

$= 450$ cm^2 V^{-1} s^{-1} for holes (p-type material)

or

$$W = 0.5\ \mu\text{m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } n\text{-type material,} \qquad (25.8)$$

and

$$W = 0.3\ \mu\text{m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } p\text{-type material,} \qquad (25.9)$$

where V is in volts and ρ is in Ω cm.

The corresponding capacitance per unit area is

$$C = \frac{\epsilon}{W} \approx 1\,[\text{pF/cm}]\,\frac{1}{W} \; . \qquad (25.10)$$

In strip detectors the capacitance is dominated by the strip-to-strip fringing capacitance of ~ 1–1.5 pF cm^{-1} of strip length at a strip pitch of 25–50 μm.

About 3.6 eV is required to create an electron-hole pair. For minimum-ionizing particles, the most probable charge deposition in a 300 μm thick silicon detector is about 4 fC (25000 electrons). Readily available photodiodes have quantum efficiences $> 70\%$ for wavelengths between 600 nm and 1 μm. UV extended photodiodes have useful efficiency down to 200 nm. In applications in which photodiodes detect light from scintillators, care must be taken so that signal from the scintillator is larger than that produced by particles going through the photodiode.

Collection time decreases with increased depletion voltage, and can be reduced further by operating the detector with "overbias," *i.e.*, a bias voltage exceeding the value required to fully deplete the device. The collection time is limited by velocity saturation at high fields; at an average field of 10^4 V/cm, the collection times is about 15 ps/μm for electrons and 30 ps/μm for holes. In typical strip detectors of 300 μm thickness, electrons are collected within about 8 ns, and holes within about 25 ns.

Position resolution is limited by transverse diffusion during charge collection (typically 5 μm for 300 μm thickness) and by knock-on electrons. Resolutions of 3–4 μm (rms) have been obtained in beam tests. In magnetic fields, the Lorentz drift can increase the spatial spread appreciably (see "Hall effect" in semiconductor textbooks).

Radiation damage occurs through two basic mechanisms:

1. Bulk damage due to displacement of atoms from their lattice sites. This leads to increased leakage current, carrier trapping, and changes in doping concentration. Displacement damage depends on the nonionizing energy loss, *i.e.*, particle type and energy. The dose should be specified as a fluence of particles of a specific type and energy.
2. Surface damage due to charge build-up in surface layers, which leads to increased surface leakage currents. In strip detectors the inter-strip isolation is affected. The effects of charge build-up are strongly dependent on the device structure and on fabrication details. Since the damage is determined directly by the absorbed energy, the dose should be specified in these units (rad or Gray).

The increase in leakage current due to bulk damage is $\Delta i = \alpha\phi$ per unit volume, where ϕ is the particle fluence and α the damage coefficient ($\alpha \approx 2 \times 10^{-17}$ A/cm for minimum ionizing protons and pions after long-term annealing; roughly the same value applies for 1 MeV neutrons). The doping concentration in n-type silicon changes as $n = n_0 \exp(-\delta\phi) - \beta\phi$, where n_0 is the initial donor concentration,

$\delta \approx 6 \times 10^{14}$ cm^2 determines donor removal, and $\beta \approx 0.03$ cm^{-1} describes acceptor creation. This leads to an initial increase in resisitivity until type-inversion changes the net doping from n to p. At this point the resistivity decreases, with a corresponding increase in depletion voltage. The safe operating limit of depletion voltage ultimately limits the detector lifetime. Strip detectors have remained functional at fluences beyond 10^{14} cm^{-2} for minimum ionizing protons. At this damage level, charge loss due to recombination and trapping also seems to become significant.

25.6. Proportional and drift chambers

Proportional chamber wire instability: The limit on the voltage V for a wire tension T, due to mechanical effects when the electrostatic repulsion of adjacent wires exceeds the restoring force of wire tension, is given by (SI units) [46]

$$V \le \frac{s}{\ell C}\sqrt{4\pi\epsilon_0 T}\ , \qquad (25.11)$$

where s, ℓ, and C are the wire spacing, length, and capacitance per unit length. An approximation to C for chamber half-gap t and wire diameter d (good for $s \lesssim t$) gives [47]

$$V \lesssim 59 T^{1/2}\left[\frac{t}{\ell} + \frac{s}{\pi\ell}\ln\left(\frac{s}{\pi d}\right)\right]\ , \qquad (25.12)$$

where V is in kV, and T is in grams-weight equivalent.

Proportional and drift chamber potentials: The potential distributions and fields in a proportional or drift chamber can usually be calculated with good accuracy from the exact formula for the potential around an array of parallel line charges q (coul/m) along z and located at $y = 0$, $x = 0, \pm s, \pm 2s, \ldots,$

$$V(x,y) = -\frac{q}{4\pi\epsilon_0}\ln\left\{4\left[\sin^2\left(\frac{\pi x}{s}\right) + \sinh^2\left(\frac{\pi y}{s}\right)\right]\right\}\ . \qquad (25.13)$$

Errors from the presence of cathodes, mechanical defects, TPC-type edge effects, *etc.*, are usually small and are beyond the scope of this review.

25.7. Time-projection chambers

Written November 1997 by M.T. Ronan (LBNL).

Detectors with long drift distances perpendicular to a multi-anode proportional plane provide three-dimensional information, with one being the time projection. A (typically strong) magnetic field parallel to the drift direction suppresses transverse diffusion ($\sigma = \sqrt{2Dt}$) by a factor

$$D(B)/D(0) = \frac{1}{1+\omega^2\tau^2}\ , \qquad (25.14)$$

where D is the diffusion coefficient, $\omega = eB/mc$ is the cyclotron frequency, and τ is the mean time between collisions. Multiple measurements of dE/dx along the particle trajectory combined with the measurement of momentum in the magnetic field allows excellent particle identification [48], as can be seen in Fig. 25.3.

A typical gas-filled TPC consists of a long uniform drift region (1–2 m) generated by a central high-voltage membrane and precision concentric cylindrical field cages within a uniform, parallel magnetic field [49]. Details of construction and electron trajectories near the anode end are shown in Fig. 25.4. Signal shaping and processing using analog storage devices or FADC's allows excellent pattern recognition, track reconstruction, and particle identification within the same detector.

Typical values:

Gas - Ar + (10–20%) CH$_4$

$E/P = 100$–$200\ V$/cm/atm

$v_{\rm drift} = 5$–7 cm/μs

$\sigma_{x \text{ or } y} = 100$–$200\ \mu$m

$\sigma_{dE/dx} = 2.5$–5.5 %

Pressure(P) = 1–8.5 atm.

$B = 1$–1.5 Tesla

$\omega\tau = 1$–8

$\sigma_z = 0.2$–1 mm

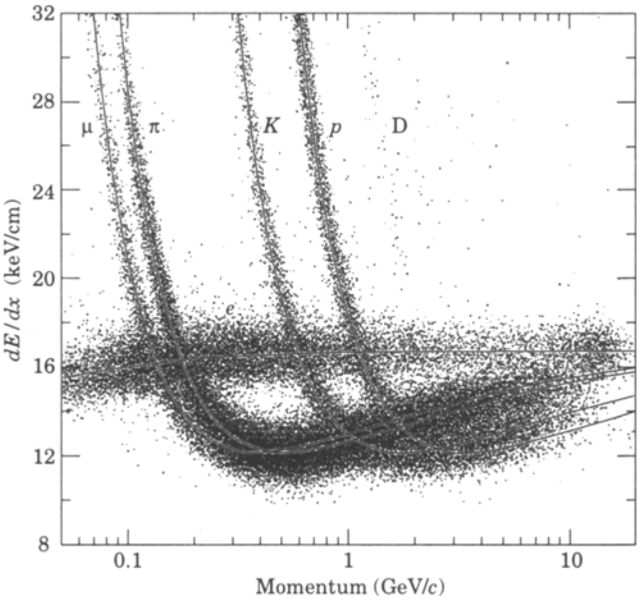

Figure 25.3: PEP4/9-TPC dE/dx measurements (185 samples @8.5 atm Ar-CH$_4$ 80–20%) in multihadron events. The electrons reach a Fermi plateau value of 1.4 times minimum. Muons from pion decays are separated from pions at low momentum; π/K are separated over all momenta except in the cross-over region. (Low-momentum protons and deuterons originate from hadron-nucleus collisions in inner materials such as the beam pipe.)

Truncated mean dE/dx resolution depends on the number and size of samples, and gas pressure:

$$\sigma_{dE/dx} \propto N^{-0.43} \times (P\ell)^{-0.32}\ . \qquad (25.15)$$

Here N is the number of samples, ℓ is the sample size, and P is the pressure. Typical dE/dx distributions are shown in Fig. 25.3. Good three-dimensional two-track resolutions of about 1–1.5 cm are routinely achieved.

$E \times B$ distortions arise from nonparallel E and B fields (see Eq. 2.6 in Ref. 49), and from the curved drift of electrons to the anode wires in the amplification region. Position measurement errors include contributions from the anode-cathode geometry, the track crossing angle (α), $E \times B$ distortions, and from the drift diffusion of electrons

$$\sigma^2_{x \text{ or } y} = \sigma_0^2 + \sigma_D^2(1+\tan^2\alpha)L/L_{\rm max} + \sigma_\alpha^2(\tan\alpha - \tan\psi)^2 \qquad (25.16)$$

where σ is the coordinate resolution, σ_0 includes the anode-cathode geometry contribution, ψ is the Lorentz angle, and L is the drift distance.

Space-charge distortions arise in high-rate environments, especially for low values of $\omega\tau$. However, they are mitigated by an effective gating grid (Fig. 25.4). Field uniformities of

$$\int (E_\perp/E)\, dz \lesssim 0.5\text{–}1 \text{ mm}\ , \qquad (25.17)$$

over 10–40 m^3 volumes have been obtained. Laser tracks and calibration events allow mapping of any remnant drift non-uniformities.

25.8. Calorimeters

Electromagnetic calorimeters: The development of electromagnetic showers is discussed in the "Passage of Particles Through Matter" section (Sec. 23 of this *Review*). Formulae are given for the approximate description of average showers, but since the physics of electromagnetic showers is well understood, detailed and reliable Monte Carlo simulation is possible. EGS4 has emerged as the standard [50].

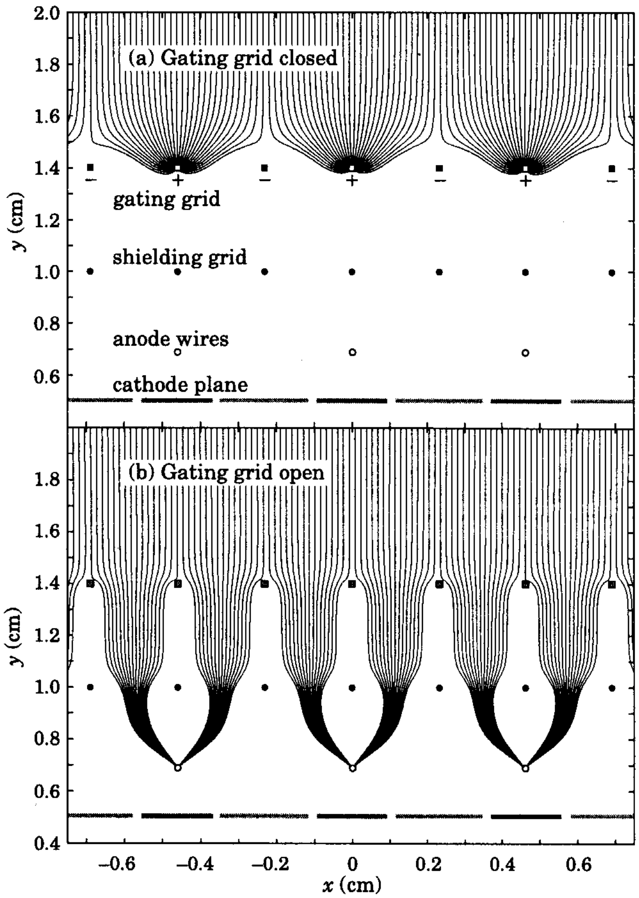

Figure 25.4: (a) Drifting electrons are collected on the gating grid until gated open by a triggering event. A shielding grid at ground potential is used to terminate the drift region. Electrons drifting through an open gating grid (b) pass through to the amplification region around the anode wires. Positive ions generated in the avalanche are detected on segmented cathode pads to provide precise measurements along the wire. The slow positive ions are blocked from entering the drift region by closing the gating grid after the electrons have drifted through.

The resolution of sampling calorimeters (hadronic and electromagnetic) is usually dominated by sampling fluctuations, leading to fractional resolution σ/E scaling inversely as the square root of the incident energy. Homogenous calorimeters, such as solid NaI(Tl), will in general not have resolution varying as $1/\sqrt{E}$. At high energies deviations from $1/\sqrt{E}$ occur because of noise, pedestal fluctuations, nonuniformities, calibration errors, and incomplete shower containment. Such effects are usually included by adding a constant term to σ/E, either in quadrature or (incorrectly) directly. In the case of the hadronic cascades discussed below, noncompensation also contributes to the constant term.

In Table 25.4 we give resolution as measured in detectors using typical EM calorimeter technologies. In almost all cases the installed calorimeters yield worse resolution than test beam prototypes for a variety of practical reasons. Where possible actual detector performance is given. For a fixed number of radiation lengths, the FWHM in sandwich detectors would be expected to be proportional to $\sqrt{t}$ for t (= plate thickness) ≥ 0.2 radiation lengths [51].

Given sufficient transverse granularity early in the calorimeter, position resolution of the order of a millimeter can be obtained.

Hadronic calorimeters [59,60]: The length scale appropriate for hadronic cascades is the nuclear interaction length, given very roughly by

$$\lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3} \ . \qquad (25.18)$$

Table 25.4: Resolution of typical electromagnetic calorimeters. E is in GeV.

Detector	Resolution
NaI(Tl) (Crystal Ball [52]; 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL [53])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31 [54]; 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS [55], LAPP-LAL [56])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module) [57]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al) [58]	$23\%/\sqrt{E}$

Longitudinal energy deposition profiles are characterized by a sharp peak near the first interaction point (from the fairly local deposition of EM energy resulting from π^0's produced in the first interaction), followed by a more gradual development with a maximum at

$$x/\lambda_I \equiv t_{\max} \approx 0.2 \ln(E/1 \text{ GeV}) + 0.7 \qquad (25.19)$$

as measured from the front of the detector.

The depth required for containment of a fixed fraction of the energy also increases logarithmically with incident particle energy. The thickness of iron required for 95% (99%) containment of cascades induced by single hadrons is shown in Fig. 25.5 [61]. Two of the sets of data are from large neutrino experiments, while the third is from a commonly used parametrization. Depths as measured in nuclear interaction lengths presumably scale to other materials. From the same data it can be concluded that the requirement that 95% of the energy in 95% of the showers be contained requires 40 to 50 cm (2.4 to 3.0 λ_I) more material material than for an average 95% containment.

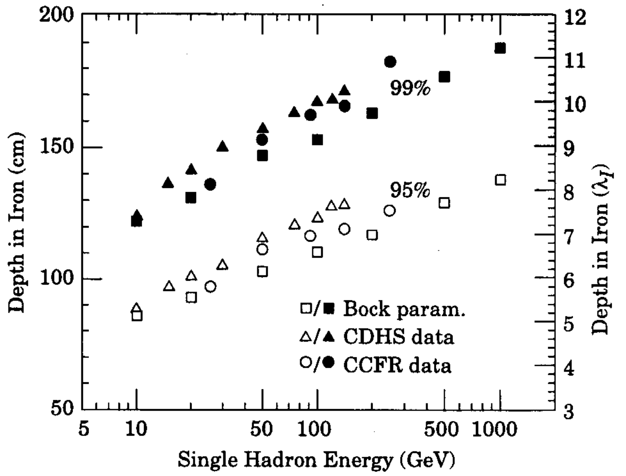

Figure 25.5: Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and the parametrization of Bock *et al.* [61].

The transverse dimensions of hadronic showers also scale as λ_I, although most of the energy is contained in a narrow core.

The energy deposit in a hadronic cascade consists of a prompt EM component due to π^0 production and a slower component mainly due to low-energy hadronic activity. In general, these energy depositions are converted to electrical signals with different efficiencies [62]. The ratio of the conversion efficiencies is usually called the intrinsic e/h ratio. If $e/h = 1.0$ the calorimeter is said to be *compensating*. If it differs from unity by more than 5% or 10%, detector performance is compromised because of fluctuations in the π^0 content of the cascades. Problems include:

a) A skewed signal distribution;

b) A response ratio for electrons and hadrons (the "e/π ratio") which is different from unity and depends upon energy;

c) A nonlinear response to hadrons (the response per GeV is proportional to the reciprocal of e/π);

d) A constant contribution to detector resolution, almost proportional to the degree of noncompensation. The coefficient relating the constant term to $|1 - e/h|$ is 14% according to FLUKA simulations, and 21% according to Wigman's calculations [59].

In most cases e/h is greater than unity, particularly if little hydrogen is present or if the gate time is short. This is because much of the low-energy hadronic energy is "hidden" in nuclear binding energy release, low-energy spallation products, *etc.* Partial correction for these losses occurs in a sampling calorimeter with thick plates, because a disproportionate fraction of electromagnetic energy is deposited in the inactive region. For this reason, a fully sensitive detector such as BGO or glass cannot be made compensating.

Compensation has been demonstrated in calorimeters with 2.5 mm scintillator sheets sandwiched between 3 mm depleted uranium plates [64] or 10 mm lead plates [65]; resolutions σ/E of $0.34/\sqrt{E}$ and $0.44/\sqrt{E}$ were obtained for these cases (E in GeV). The former was shown to be linear to within 2% over three orders of magnitude in energy, with approximately Gaussian signal distributions.

25.9. Measurement of particle momenta in a uniform magnetic field [71,72]

The trajectory of a particle with momentum p (in GeV/c) and charge ze in a constant magnetic field $\vec{B}$ is a helix, with radius of curvature R and pitch angle λ. The radius of curvature and momentum component perpendicular to $\vec{B}$ are related by

$$p \cos\lambda = 0.3\, z\, B\, R\ , \tag{25.20}$$

where B is in tesla and R is in meters.

The distribution of measurements of the curvature $k \equiv 1/R$ is approximately Gaussian. The curvature error for a large number of uniformly spaced measurements on the trajectory of a charged particle in a uniform magnetic field can be approximated by

$$(\delta k)^2 = (\delta k_{\rm res})^2 + (\delta k_{\rm ms})^2\ , \tag{25.21}$$

where δk = curvature error

$\delta k_{\rm res}$ = curvature error due to finite measurement resolution

$\delta k_{\rm ms}$ = curvature error due to multiple scattering.

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

$$\delta k_{\rm res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}\ , \tag{25.22}$$

where N = number of points measured along track

L' = the projected length of the track onto the bending plane

ϵ = measurement error for each point, perpendicular to the trajectory.

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.

For arbitrary spacing of coordinates s_i measured along the projected trajectory and with variable measurement errors ϵ_i the curvature error $\delta k_{\rm res}$ is calculated from:

$$(\delta k_{\rm res})^2 = \frac{4}{w}\ \frac{V_{ss}}{V_{ss}V_{s^2s^2} - (V_{ss^2})^2}\ , \tag{25.23}$$

where V are covariances defined as $V_{s^m s^n} = \langle s^m s^n\rangle - \langle s^m\rangle\langle s^n\rangle$ with $\langle s^m\rangle = w^{-1}\sum(s_i{}^m/\epsilon_i{}^2)$ and $w = \sum \epsilon_i{}^{-2}$.

The contribution due to multiple Coulomb scattering is approximately

$$\delta k_{\rm ms} \approx \frac{(0.016)({\rm GeV}/c)z}{Lp\beta\cos^2\lambda}\sqrt{\frac{L}{X_0}}\ , \tag{25.24}$$

where p = momentum (GeV/c)

z = charge of incident particle in units of e

L = the total track length

X_0 = radiation length of the scattering medium (in units of length; the X_0 defined elsewhere must be multiplied by density)

β = the kinematic variable v/c.

More accurate approximations for multiple scattering may be found in the section on Passage of Particles Through Matter (Sec. 23 of this *Review*). The contribution to the curvature error is given approximately by $\delta k_{\rm ms} \approx 8 s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ is defined there.

25.10. Superconducting solenoids for collider detectors

Revised October 1997 by R.D. Kephart (FNAL).

25.10.1. ***Basic (approximate) equations***: In all cases SI units are assumed, so that B is in tesla, E is in joules, dimensions are in meters, and $\mu_0 = 4\pi \times 10^{-7}$.

Magnetic field: The magnetic field at the center of a solenoid of length L and radius R, having N total turns and a current I is

$$B(0,0) = \frac{\mu_0 N I}{\sqrt{L^2 + 4R^2}}\ . \tag{25.25}$$

Stored energy: The energy stored in the magnetic field of any magnet is calculated by integrating B^2 over all space:

$$E = \frac{1}{2\mu_0}\int B^2 dV\ . \tag{25.26}$$

For a solenoid with an iron flux return in which the magnetic field is $< 2T$, the field in the aperture is approximately uniform and equal to $\mu_0 NI/L$. If the thickness of the coil is small, (which is the case if it is superconducting), then

$$E \approx (\pi/2\mu_0)B^2R^2L\ . \tag{25.27}$$

Cost of a superconducting solenoid [73]:

$$\text{Cost (in M\$)} = 0.523\,[(E/(1\ \text{MJ})]^{0.662} \tag{25.28}$$

Magnetostatic computer programs: It is too difficult to solve the Biot-Savart equation for a magnetic circuit which includes iron components and so iterative computer programs are used. These include POISSON, TOSCA [74], and ANSYS [75].

25.10.2. ***Scaling laws for thin solenoids***: For a detector in which the calorimetry is outside the aperture of the solenoid, the coil must be thin in terms of radiation and absorption lengths. This usually means that the coil is superconducting and that the vacuum vessel encasing it is of minimum real thickness and fabricated of a material with long radiation length. There are two major contributers to the thickness of a thin solenoid:

1. The conductor, consisting of the current-carrying superconducting material (usually Cu/Nb-Ti) and the quench protecting stabilizer (usually aluminum), is wound on the inside of a structural support cylinder (usually aluminum also). This package typically represents about 60% of the total thickness in radiation lengths. The thickness scales approximately as B^2R.
2. Approximately another 25% of the thickness of the magnet comes from the outer cylindrical shell of the vacuum vessel. Since this shell is susceptible to buckling collapse, its thickness is determined by the diameter, length, and the modulus of the material of which it is fabricated. When designing this shell to a typical standard, the real thickness is

$$t = P_c D^{2.5}[(L/D) - 0.45(t/D)^{0.5}]/2.6Y^{0.4}\ , \tag{25.29}$$

where t = shell thickness (in), D = shell diameter (in), L = shell length (in), Y = modulus of elasticity (psi), and P_c = design collapse pressure (= 30 psi). For most large-diameter detector solenoids, the thickness to within a few percent is given by [76]

$$t = P_c D^{2.5}(L/D)/2.6Y^{0.4}\ . \tag{25.30}$$

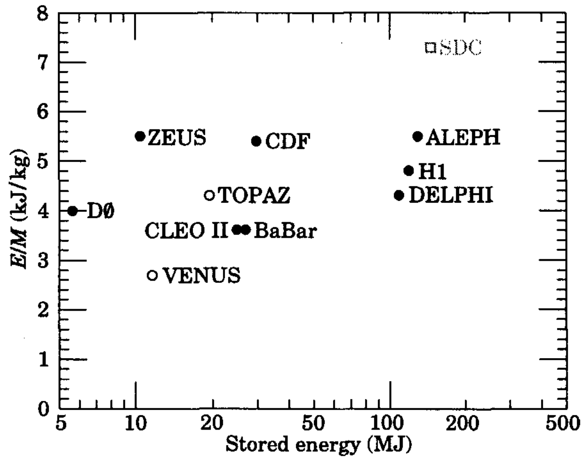

Figure 25.6: Ratio of stored energy to cold mass for existing thin detector solenoids. Solenoids in decommissioned detectors are indicated by open circles.

25.10.3. ***Properties of collider detector solenoids*:** The physical dimensions, central field, stored energy and thickness in radiation lengths normal to the beam line of the superconducting solenoids associated with the major colliders are given in Table 25.5.

Table 25.5: Properties of superconducting collider detector solenoids.

Experiment–Lab	Field (T)	Bore Dia (m)	Length (m)	Energy (MJ)	Thickness (X_0)
CDF–Fermilab	1.5	2.86	5.07	30	0.86
DØ –Fermilab	2.0	1.06	2.73	5.6	0.87
BaBar–SLAC	1.5	2.80	3.46	27.0	< 1.4
Topaz–KEK	1.2	2.72	5.4	19.5	0.70
Venus–KEK	0.75	3.4	5.64	12	0.52
Cleo II–Cornell	1.5	2.9	3.8	25	2.5
Aleph–CERN	1.5	5.0	7.0	130	1.7
Delphi–CERN	1.2	5.2	7.4	109	4.0
H1–DESY	1.2	5.2	5.75	120	1.2
Zeus–DESY	1.8	1.72	2.85	10.5	0.9

The ratio of stored energy to cold mass (E/M) is a useful performance measure. One would like the cold mass to be as small as possible to minimize the thickness, but temperature rise during a quench must also be minimized. Ratios as large as 8 kJ/kg may be possible (final temperature of 80 K after a fast quench with homogenous energy dump), but some contingency is desirable. This quantity is shown as a function of total stored energy for some major collider detectors in Fig. 25.6.

25.11. Other observations

dE/dx resolution in argon: Particle identification by dE/dx is dependent on the width of the distribution. For relativistic incident particles with charge e in a multiple-sample Ar gas counter with no lead [66],

$$\left.\frac{dE}{dx}\right|_{\rm FWHM} \Big/ \left.\frac{dE}{dx}\right|_{\rm most\ probable} = 0.96\,N^{-0.46}(xp)^{-0.32}\,, \tag{25.31}$$

where N = number of samples, x = thickness per sample (cm), p = pressure (atm.). Most commonly used chamber gases (except Xe) give approximately the same resolution.

Free electron drift velocities in liquid ionization chambers [67–70]: Velocity as a function of electric field strength is given in

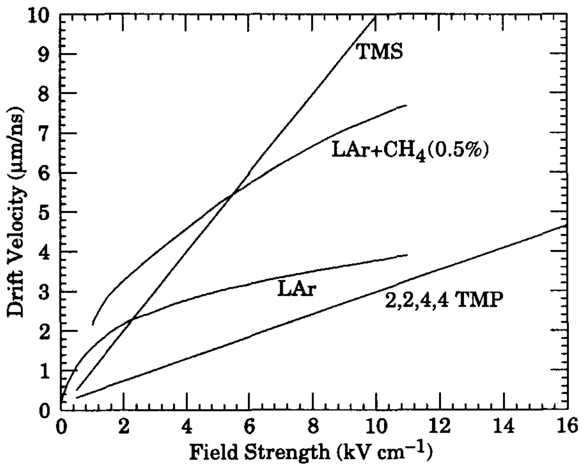

Figure 25.7: Electron drift velocity as a function of field strength for commonly used liquids.

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26. RADIOACTIVITY AND RADIATION PROTECTION

Revised March 1998 by R.J. Donahue (LBNL) and A. Fassò (SLAC).

26.1. Definitions

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

- **Unit of activity** = becquerel (curie):

  $1\ \text{Bq} = 1\ \text{disintegration s}^{-1}\ [= 1/(3.7 \times 10^{10})\ \text{Ci}]$

- **Unit of absorbed dose** = gray (rad):

  $1\ \text{Gy} = 1\ \text{joule kg}^{-1}\ (= 10^4\ \text{erg g}^{-1} = 100\ \text{rad})$

  $= 6.24 \times 10^{12}\ \text{MeV kg}^{-1}$ deposited energy

- **Unit of exposure**, the quantity of x- or γ- radiation at a point in space integrated over time, in terms of charge of either sign produced by showering electrons in a small volume of air about the point:

  $= 1\ \text{coul kg}^{-1}$ of air (roentgen; $1\ R = 2.58 \times 10^{-4}\ \text{coul kg}^{-1}$)

  $= 1\ \text{esu cm}^{-3}$($= 87.8$ erg released energy per g of air)

Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving. This unit is somewhat historical, but appears on many measuring instruments.

- **Unit of equivalent dose** (for biological damage) = sievert [= 100 rem (roentgen equivalent for man)]: Equivalent dose in Sv = absorbed dose in grays × w_R, where w_R (radiation weighting factor, formerly the quality factor Q) expresses long-term risk (primarily cancer and leukemia) from low-level chronic exposure. It depends upon the type of radiation and other factors, as follows [2]:

Table 26.1: Radiation weighting factors.

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

26.2. Radiation levels [3]

- **Natural annual background,** all sources: Most world areas, whole-body equivalent dose rate ≈ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) in certain areas. U.S. average ≈ 3.6 mSv, including ≈ 2 mSv (≈ 200 mrem) from inhaled natural radioactivity, mostly radon and radon daughters (0.1–0.2 mSv in open areas. Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines).

- **Cosmic ray background** in counters (Earth's surface): $\sim 1\ \text{min}^{-1}\ \text{cm}^{-2}\ \text{sr}$. For more accurate estimates and details, see the Cosmic Rays section (Sec. 20 of this *Review*).

- **Fluxes** (per cm^2) to deposit one Gy, assuming uniform irradiation:

  ≈ **(charged particles)** $6.24 \times 10^9/(dE/dx)$, where dE/dx (MeV g^{-1} cm^2), the energy loss per unit length, may be obtained from the Mean Range and Energy Loss figures.

  ≈ $3.5 \times 10^9\ \text{cm}^{-2}$ minimum-ionizing singly-charged particles in carbon.

  ≈ **(photons)** $6.24 \times 10^9/[Ef/\lambda]$, for photons of energy E (MeV), attenuation length λ (g cm^{-2}) (see Photon Attenuation Length figure), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \lambda$ but large enough to contain the secondary electrons.

  ≈ 2×10^{11} photons cm^{-2} for 1 MeV photons on carbon ($f \approx 1/2$).

  (Quoted fluxes are good to about a factor of 2 for all materials.)

- **Recommended limits to exposure of radiation workers (whole-body dose):***

  CERN: 15 mSv yr^{-1}

  U.K.: 15 mSv yr^{-1}

  U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})†

- **Lethal dose:** Whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) 2.5–3.0 Gy (250–300 rads), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

26.3. Prompt neutrons at accelerators

26.3.1. ***Electron beams***: At electron accelerators neutrons are generated via photonuclear reactions from bremsstrahlung photons. Neutron yields from semi-infinite targets per unit electron beam power are plotted in Fig. 26.1 as a function of electron beam energy [4]. In the photon energy range 10–30 MeV neutron production results from the giant photonuclear resonance mechanism. Neutrons are produced roughly isotropically (within a factor of 2) and with a Maxwellian energy distribution described as:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T} , \qquad (26.1)$$

where T is the nuclear temperature characteristic of the target nucleus, generally in the range of T = 0.5–1.0 MeV. For higher energy photons the quasi-deuteron and photopion production mechanisms become important.

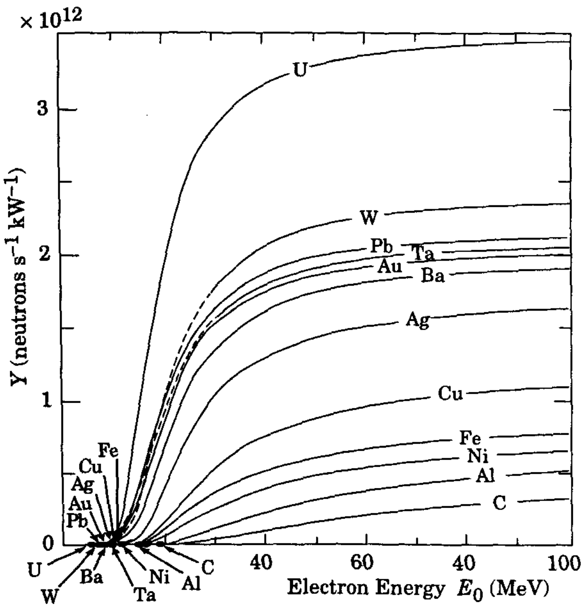

Figure 26.1: Neutron yields from semi-infinite targets, per kW of electron beam power, as a function of electron beam energy, disregarding target self-shielding.

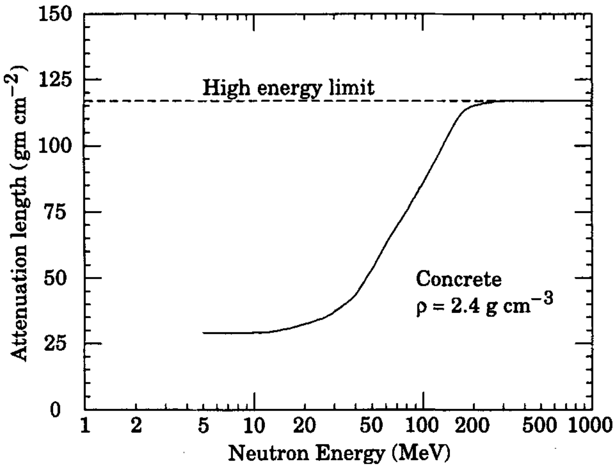

Figure 26.3: The variation of the attenuation length for monoenergetic neutrons in concrete as a function of neutron energy [5].

26.3.2. ***Proton beams***: At proton accelerators neutron yields emitted per incident proton by different target materials are roughly independent [5] of proton energy between 20 MeV and 1 GeV and are given by the ratio C:Al:Cu-Fe:Sn:Ta-Pb = 0.3 : 0.6 : 1.0 : 1.5 : 1.7. Above 1 GeV neutron yield [6] is proportional to E^m, where $0.80 \leq m \leq 0.85$.

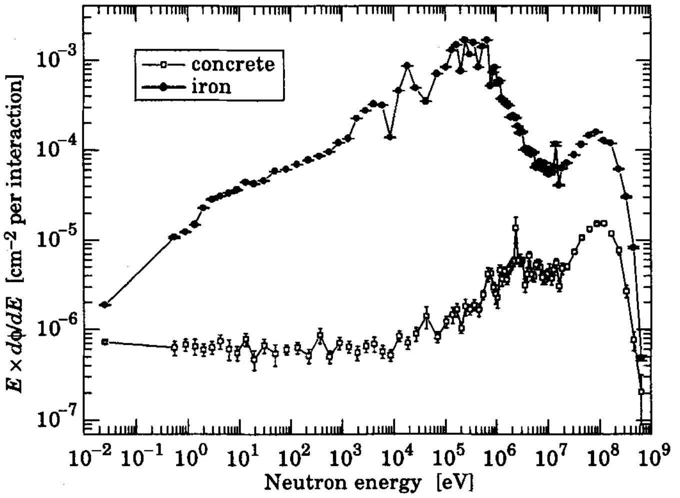

Figure 26.2: Calculated neutron spectrum from 205 GeV/c hadrons (2/3 protons and 1/3 π^+) on a thick copper target. Spectra are evaluated at 90° to beam and through 80 cm of normal density concrete or 40 cm of iron.

A typical neutron spectrum [7] outside a proton accelerator concrete shield is shown in Fig. 26.2. The shape of these spectra are generally characterized as having a thermal-energy peak which is very dependent on geometry and the presence of hydrogenic material, a low-energy evaporation peak around 2 MeV, and a high-energy spallation shoulder.

Letaw's [8] formula for the energy dependence of the inelastic proton cross-section (asymptotic values given in Table 6.1) for $E < 2$ GeV is:

$$\sigma(E) = \sigma_{\rm asympt}\left[1 - 0.62e^{-E/200}\sin(10.9E^{-0.28})\right] , \qquad (26.2)$$

and for $E > 2$ GeV:

$$\sigma_{\rm asympt} = 45A^{0.7}\left[1 + 0.016\sin(5.3 - 2.63\ln\, A)\right] , \qquad (26.3)$$

where σ is in mb, E is the proton energy in MeV and A is the mass number.

The neutron-attenuation length, λ, is shown in Fig. 26.3 for monoenergetic broad-beam conditions. These values give a satisfactory representation at depths greater than 1 m in concrete.

26.4. Dose conversion factors

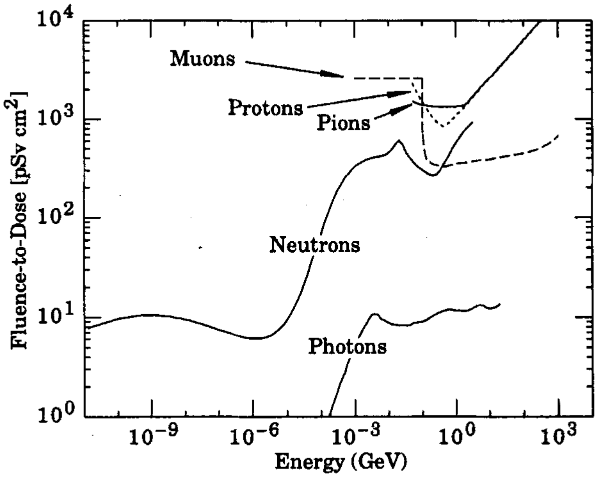

Figure 26.4: Fluence to dose equivalent conversion factors for various particles.

Fluence to dose equivalent factors are given in Fig. 26.4 for photons [9], neutrons [10], muons [11], protons and pions [12]. These factors can be used for converting particle fluence to dose for personnel protection purposes.

26.5. Accelerator-induced activity

The dose rate at 1 m due to spallation-induced activity by high energy hadrons in a 1 g medium atomic weight target can be estimated [13] from the following expression:

$$D = D_0\ \Phi\ \ln[(T + t)/t] , \qquad (26.4)$$

where T is the irradiation time, t is the decay time since irradiation, Φ is the flux of irradiating hadrons (hadrons cm^{-2} s^{-1}) and D_0 has a value of 5.2×10^{-17} [(Sv hr^{-1})/(hadron cm^{-2} s^{-1})]. This relation is essentially independent of hadron energy above 200 MeV.

Dose due to accelerator-produced induced activity can also be estimated with the use of "ω factors" [5]. These factors give the dose rate per unit star density (inelastic reaction for $E > 50$ MeV) after a 30-day irradiation and 1-day decay. The ω factor for steel or iron is $\simeq 3 \times 10^{-12}$ (Sv cm^3/star). This does not include possible contributions from thermal-neutron activation. Induced activity in concrete can vary widely depending on concrete composition, particularly with the concentration of trace quantities such as sodium. Additional information can be found in Barbier [14].

26.6. Photon sources

The dose rate from a gamma point source of C Curies emitting one photon of energy $0.07 < E < 4$ MeV per disintegration at a distance of 30 cm is 6CE (rem/hr), or 60CE (mSv/hr), ±20%.

The dose rate from a semi-infinite uniform photon source of specific activity C (μCi/g) and gamma energy E (MeV) is $1.07CE$ (rem/hr), or $10.7CE$ (mSv/hr).

26.7. Radiation levels in detectors at hadron colliders

An SSC Central Design Group task force studied the radiation levels to be expected in SSC detectors [15]. The study focused on scaling with energy, distance, and angle. As such, it is applicable to future detectors such as those at the LHC. Although superior detector-specific calculations have since been made, the scaling is in most cases not evident, and so the SSC results have some relevance. The SSC/CDG model assumed

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathscr{L} = 10^{33}$ cm^{-2}s^{-1}, and the pp inelastic cross section is $\sigma_{\text{inel}} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1};
- All radiation comes from pp collisions at the interaction point;
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, which is taken as independent of pseudorapidity:

$$\frac{d^2N_{\text{ch}}}{d\eta dp_\perp} = H\, f(p_\perp) \tag{26.5}$$

(where $p_\perp = p \sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp \rangle)$; in the worst case this approximation introduces an error of less than 10%;

- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum;
- At the SSC ($\sqrt{s} = 40$ TeV), $H \approx 7.5$ and $\langle p_\perp \rangle \approx 0.6$ GeV/c; assumed values at other energies are given in Table 26.3. Together with the model discussed above, these values are thought to describe particle production to within a factor of two or better.

It then follows that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\text{ch}}}{da} = \frac{1.2 \times 10^8\,\text{s}^{-1}}{r_\perp^2} \; . \tag{26.6}$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may thus be rewritten as dose rate,

$$\dot{D} = \frac{0.4\ \text{MGy yr}^{-1}}{(r_\perp/1\ \text{cm})^2} \; . \tag{26.7}$$

If a magnetic field is present, "loopers" may increase this dose rate by a factor of two ore more.

In a medium in which cascades can develop, the ionizing dose or neutron fluence is proportional to dN_{ch}/da multiplied by $\langle E \rangle^\alpha$, where $\langle E \rangle$ is the mean energy of the particles going through da and the power α is slightly less than unity. Since $E \approx p = p_\perp / \sin\theta$ and $r_\perp = r \sin\theta$, the above expression for dN_{ch}/da becomes

$$\text{Dose or fluence}^{\ddagger} = \frac{A}{r^2} \cosh^{2+\alpha} \eta = \frac{A}{r^2 \sin^{2+\alpha}\theta} \; . \tag{26.8}$$

The constant A contains the total number of interactions $\sigma_{\text{inel}} \int \mathscr{L} dt$, so the ionizing dose or neutron fluence at another accelerator scales as $\sigma_{\text{inel}} \int \mathscr{L} dt\, H \langle p_\perp \rangle^\alpha$.

The dose or fluence in a calorimeter scales as $1/r^2$, as does the neutron fluence inside a central cavity with characteristic dimension r.

Under all conditions so far studied, the neutron spectrum shows a broad log-normal distribution peaking at just under 1 MeV. In a 2 m radius central cavity of a detector with coverage down to $|\eta| = 3$, the average neutron flux is 2×10^{12} cm^{-2}yr^{-1}, including secondary scattering contributions.

Values of A and α are given in Table 26.2 for several relevant situations. Examples of scaling to other accelerators are given in Table 26.3. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

The constant A includes factors evaluated with cascade simulation programs as well as constants describing particle production at the interaction point. It is felt that each could introduce an error as large as a factor of two in the results.

Table 26.2: Coefficients $A/(100\ \text{cm})^2$ and α for the evaluation of calorimeter radiation levels at cascade maxima under SSC nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2 \sin^{2+\alpha}\theta)$.

Quantity	$A/(100\,\text{cm})^2$	Units	$\langle p_\perp \rangle$	α
Neutron flux	1.5×10^{12}	cm^{-2}yr^{-1}	0.6 GeV/c	0.67
Dose rate from photons	124	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

Table 26.3: A rough comparison of beam-collision induced radiation levels at the Tevatron, high-luminosity LHC, SSC, and a possible 100 TeV machine [16].

	Tevatron	LHC	SSC	100 TeV
$\sqrt{s}$ (TeV)	1.8	15.4	40	100
$\mathscr{L}_{\text{nom}}$ (cm^{-2}s^{-1})	2×10^{30}	1.7×10^{34}[a]	1×10^{33}	1×10^{34}
σ_{inel}	56 mb	84 mb	100 mb	134 mb
H	3.9	6.2	7.5	10.6
$\langle p_\perp \rangle$ (GeV/c)	0.46	0.55	0.60	0.70
Relative dose rate[b]	5×10^{-4}	11	1	20

[a] High-luminosity option.

[b] Proportional to $\mathscr{L}_{\text{nom}}\, \sigma_{\text{inel}}\, H\, \langle p_\perp \rangle^{0.7}$

Footnotes:

[*] The ICRP recomendation [2] is 20 mSv yr^{-1} averaged over 5 years, with the dose in any one year $\leq$ 50 mSv.

[†] Many laboratories in the U.S. and elsewhere set lower limits.

[‡] *Dose* is the time integral of *dose rate*, and *fluence* is the time integral of *flux*.

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27. COMMONLY USED RADIOACTIVE SOURCES

Table 27.1. Revised November 1993 by E. Browne (LBNL).

			Particle		Photon	
Nuclide	Half-life	Type of decay	Energy (MeV)	Emission prob.	Energy (MeV)	Emission prob.
$^{22}_{11}$Na	2.603 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K x rays	26%
$^{55}_{26}$Fe	2.73 y	EC			Mn K x rays:	
					0.00590	24.4%
					0.00649	2.86%
$^{57}_{27}$Co	0.744 y	EC			0.014	9%
					0.122	86%
					0.136	11%
					Fe K x rays	58%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K x rays	44%
→ $^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
→ $^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
→ $^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K x rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	65%
			0.388 e^-	6%	In K x rays	97%
$^{137}_{55}$Cs	30.2 y	β^-	0.514 e^-	94%	0.662	85%
			1.176 e^-	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K x rays	121%
$^{207}_{83}$Bi	31.8 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K x rays	78%
$^{228}_{90}$Th	1.912 y	6α:	5.341 to 8.785		0.239	44%
		3β^-:	0.334 to 2.246		0.583	31%
					2.614	36%
(→$^{224}_{88}$Ra → $^{220}_{86}$Rn → $^{216}_{84}$Po → $^{212}_{82}$Pb → $^{212}_{83}$Bi → $^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L x rays	38%
$^{241}_{95}$Am/Be	432.2 y	6×10^{-5} neutrons (4–8 MeV) and $4 \times 10^{-5}\gamma$'s (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L x rays	$\sim$ 9%
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%) $\approx$ 20 γ's/fission; 80% < 1 MeV $\approx$ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

"Emission probability" is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^{\pm}$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986), recent *Nuclear Data Sheets*, and *X-ray and Gamma-ray Standards for Detector Calibration*, IAEA-TECDOC-619 (1991).

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28. PROBABILITY

Revised May 1996 by D.E. Groom (LBNL) and F. James (CERN).

28.1. General [1–5]

Let x be a possible outcome of an observation. The probability of x is the relative frequency with which that outcome occurs out of a (possibly hypothetical) large set of similar observations. If x can take any value from a *continuous* range, we write $f(x;\theta)\,dx$ as the probability of observing x between x and $x+dx$. The function $f(x;\theta)$ is the *probability density function* (p.d.f.) for the *random variable* x, which may depend upon one or more parameters θ. If x can take on only *discrete* values (*e.g.*, the non-negative integers), then $f(x;\theta)$ is itself a probability, but we shall still call it a p.d.f. The p.d.f. is always normalized to unit area (unit sum, if discrete). Both x and θ may have multiple components and are then often written as column vectors. If θ is unknown and we wish to estimate its value from a given set of data measuring x, we may use statistics (see Sec. 29).

The *cumulative distribution function* $F(a)$ is the probability that $x \le a$:

$$F(a) = \int_{-\infty}^{a} f(x)\,dx \ . \tag{28.1}$$

Here and below, if x is discrete-valued, the integral is replaced by a sum. The endpoint a is expressly included in the integral or sum. Then $0 \le F(x) \le 1$, $F(x)$ is nondecreasing, and $\text{Prob}(a < x \le b) = F(b) - F(a)$. If x is discrete, $F(x)$ is flat except at allowed values of x, where it has discontinuous jumps equal to $f(x)$.

Any function of random variables is itself a random variable, with (in general) a different p.d.f. The *expectation value* of any function $u(x)$ is

$$E\left[u(x)\right] = \int_{-\infty}^{\infty} u(x)\,f(x)\,dx \ , \tag{28.2}$$

assuming the integral is finite. For $u(x)$ and $v(x)$ any two functions of x, $E(u+v) = E(u) + E(v)$. For c and k constants, $E(cu+k) = cE(u) + k$.

The nth moment of a distribution is

$$\alpha_n \equiv E(x^n) = \int_{-\infty}^{\infty} x^n f(x) dx \ , \tag{28.3a}$$

and the nth moment about the mean of x, α_1, is

$$m_n \equiv E[(x-\alpha_1)^n] = \int_{-\infty}^{\infty} (x-\alpha_1)^n f(x) dx \ . \tag{28.3b}$$

The most commonly used moments are the mean μ and variance σ^2:

$$\mu \equiv \alpha_1 \tag{28.4a}$$

$$\sigma^2 \equiv \text{Var}(x) \equiv m_2 = \alpha_2 - \mu^2 \ . \tag{28.4b}$$

The mean is the location of the "center of mass" of the probability density function, and the variance is a measure of the square of its width. Note that $\text{Var}(cx+k) = c^2\text{Var}(x)$.

Any odd moment about the mean is a measure of the skewness of the p.d.f. The simplest of these is the dimensionless coefficient of skewness $\gamma_1 \equiv m_3/\sigma^3$.

Besides the mean, another useful indicator of the "middle" of the probability distribution is the *median* x_{med}, defined by $F(x_{\text{med}}) = 1/2$; *i.e.*, half the probability lies above and half lies below x_{med}. For a given *sample* of events, x_{med} is the value such that half the events have larger x and half have smaller x (not counting any that have the same x as the median). If the sample median lies between two observed x values, it is set by convention halfway between them. If the p.d.f. for x has the form $f(x-\mu)$ and μ is both mean and median, then for a large number of events N, the variance of the median approaches $1/[4Nf^2(0)]$, provided $f(0) > 0$.

Let x and y be two random variables with a joint p.d.f. $f(x,y)$. The *marginal* p.d.f. of x (the distribution of x with y unobserved) is

$$f_1(x) = \int_{-\infty}^{\infty} f(x,y)\,dy \ , \tag{28.5}$$

and similarly for the marginal p.d.f. $f_2(y)$. We define the *conditional* p.d.f. of x, given fixed y, by

$$f_3(y|x)\,f_1(x) = f(x,y) \ . \tag{28.6a}$$

Similarly, the conditional p.d.f. of y, given fixed x, is

$$f_4(x|y)\,f_2(y) = f(x,y) \ . \tag{28.6b}$$

From these definitions we immediately obtain Bayes' theorem [2]:

$$f_4(x|y) = \frac{f_3(y|x)\,f_1(x)}{f_2(y)} = \frac{f_3(y|x)\,f_1(x)}{\int f_3(y|x)\,f_1(x)\,dx} \ . \tag{28.7}$$

The mean of x is

$$\mu_x = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\,f(x,y)\,dx\,dy = \int_{-\infty}^{\infty} x\,f_1(x)\,dx \ , \tag{28.8}$$

and similarly for y. The *correlation* between x and y is a measure of the dependence of one on the other:

$$\rho_{xy} = E\left[(x-\mu_x)(y-\mu_y)\right]/\sigma_x\,\sigma_y = \text{Cov}(x,y)/\sigma_x\,\sigma_y \ , \tag{28.9}$$

where σ_x and σ_y are defined in analogy with Eq. (28.4*b*). It can be shown that $-1 \le \rho_{xy} \le 1$. Here "Cov" is the covariance of x and y, a 2-dimensional analogue of the variance.

Two random variables are *independent* if and only if

$$f(x,y) = f_1(x)\,f_2(y) \ . \tag{28.10}$$

If x and y are independent then $\rho_{xy} = 0$; the converse is not necessarily true except for Gaussian-distributed x and y. If x and y are independent, $E[u(x)\,v(y)] = E[u(x)]\,E[v(y)]$, and $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)$; otherwise, $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)+2\text{Cov}(x,y)$, and $E(u\,v)$ does not factor.

In a *change of continuous random variables* from $\boldsymbol{x} \equiv (x_1,\ldots,x_n)$, with p.d.f. $f(\boldsymbol{x}) = f(x_1,\ldots,x_n)$, to $\boldsymbol{y} \equiv (y_1,\ldots,y_n)$, a one-to-one function of the x_i's, the p.d.f. $g(\boldsymbol{y}) = g(y_1,\ldots,y_n)$ is found by substitution for $(x_1,\ldots,x_n)$ in f followed by multiplication by the absolute value of the Jacobian of the transformation; that is,

$$g(\boldsymbol{y}) = f\left[w_1(\boldsymbol{y}),\ldots,w_n(\boldsymbol{y})\right]|J| \ . \tag{28.11}$$

The functions w_i express the *inverse* transformation, $x_i = w_i(\boldsymbol{y})$ for $i = 1,\ldots,n$, and $|J|$ is the absolute value of the determinant of the square matrix $J_{ij} = \partial x_i/\partial y_j$. If the transformation from $\boldsymbol{x}$ to $\boldsymbol{y}$ is not one-to-one, the situation is more complex and a unique solution may not exist. For example, if the change is to $m < n$ variables, then a given $\boldsymbol{y}$ may correspond to more than one $\boldsymbol{x}$, leading to multiple integrals over the contributions [1].

To change variables for discrete random variables simply substitute; no Jacobian is necessary because now f is a probability rather than a probability density.

If f depends upon a parameter set $\boldsymbol{\alpha}$, a change to a different parameter set $\phi_i = \phi_i(\boldsymbol{\alpha})$ is made by simple substitution; no Jacobian is used.

28.2. Characteristic functions

The characteristic function $\phi(u)$ associated with the p.d.f. $f(x)$ is essentially its (inverse) Fourier transform, or the expectation value of $\exp(iux)$:

$$\phi(u) = E(e^{iux}) = \int_{-\infty}^{\infty} e^{iux} f(x) dx \ . \tag{28.12}$$

It is often useful, and several of its properties follow [1].

It follows from Eqs. (28.3*a*) and (28.12) that the nth moment of the distribution $f(x)$ is given by

$$i^{-n}\frac{d^n\phi}{du^n}\bigg|_{u=0} = \int_{-\infty}^{\infty} x^n f(x) dx = \alpha_n \ . \tag{28.13}$$

Thus it is often easy to calculate all the moments of a distribution defined by $\phi(u)$, even when $f(x)$ is difficult to obtain.

If $f_1(x)$ and $f_2(y)$ have characteristic functions $\phi_1(u)$ and $\phi_2(u)$, then the characteristic function of the weighted sum $ax + by$ is $\phi_1(au)\phi_2(bu)$. The addition rules for common distributions (*e.g.*, that the sum of two numbers from Gaussian distributions also has a Gaussian distribution) easily follow from this observation.

Let the (partial) characteristic function corresponding to the conditional p.d.f. $f_2(x|z)$ be $\phi_2(u|z)$, and the p.d.f. of z be $f_1(z)$. The characteristic function after integration over the conditional value is

$$\phi(u) = \int \phi_2(u|z)\, f_1(z) dz \ . \tag{28.14}$$

Suppose we can write ϕ_2 in the form

$$\phi_2(u|z) = A(u) e^{ig(u)z} \ . \tag{28.15}$$

Then

$$\phi(u) = A(u)\phi_1(g(u)) \ . \tag{28.16}$$

The semi-invariants κ_n are defined by

$$\phi(u) = \exp\left(\sum_1^\infty \frac{\kappa_n}{n!}(iu)^n\right) = \exp\left(i\kappa_1 u - \tfrac{1}{2}\kappa_2 u^2 + \ldots\right) \ . \tag{28.17}$$

The κ_n's are related to the moments α_n and m_n. The first few relations are

$$\begin{aligned}
&\kappa_1 = \alpha_1 \ (= \mu, \text{ the mean}) \\
&\kappa_2 = m_2 \ = \alpha_2 - \alpha_1^2 \ (= \sigma^2, \ \text{ the variance}) \\
&\kappa_3 = m_3 = \alpha_3 - 3\alpha_1\alpha_2 + 2\alpha_1^2 \ .
\end{aligned} \tag{28.18}$$

28.3. Some probability distributions

Table 28.1 gives a number of common probability density functions and corresponding characteristic functions, means, and variances. Further information may be found in Refs. 1–6; Ref. 6 has particularly detailed tables. Monte Carlo techniques for generating each of them may be found in our Sec. 30.4. We comment below on all except the trivial uniform distribution.

28.3.1. ***Binomial distribution***: A random process with exactly two possible outcomes is called a *Bernoulli* process. If the probability of obtaining a certain outcome (a "success") in each trial is p, then the probability of obtaining exactly r successes ($r = 0, 1, 2, \ldots, n$) in n trials, without regard to the order of the successes and failures, is given by the binomial distribution $f(r; n, p)$ in Table 28.1. If r successes are observed in n_r trials with probability p of a success, and if s successes are observed in n_s similar trials, then $t = r + s$ is also binomial with $n_t = n_r + n_s$.

28.3.2. ***Poisson distribution***: The Poisson distribution $f(r;\mu)$ gives the probability of finding exactly r events in a given interval of x (*e.g.*, space and time) when the events occur independently of one another and of x at an average rate of μ per the given interval. The variance σ^2 equals μ. It is the limiting case $p \to 0$, $n \to \infty$, $np = \mu$ of the binomial distribution. The Poisson distribution approaches the Gaussian distribution for large μ.

Two or more Poisson processes (*e.g.*, ***signal*** + ***background***, with parameters μ_s and μ_b) that independently contribute amounts n_s and n_b to a given measurement will produce an observed number $n = n_s + n_b$, which is distributed according to a new Poisson distribution with parameter $\mu = \mu_s + \mu_b$.

28.3.3. ***Normal or Gaussian distribution***: The normal (or Gaussian) probability density function $f(x; \mu, \sigma^2)$ given in Table 28.1 has mean $\overline{x} = \mu$ and variance σ^2. Comparison of the characteristic function $\phi(u)$ given in Table 28.1 with Eq. (28.17) shows that all semi-invariants κ_n beyond κ_2 vanish; this is a unique property of the Gaussian distribution. Some properties of the distribution are:

rms deviation = σ

probability x in the range $\mu \pm \sigma = 0.6827$

probability x in the range $\mu \pm 0.6745\sigma = 0.5$

expection value of $|x - \mu|$, $E(|x - \mu|) = (2/\pi)^{1/2}\sigma = 0.7979\sigma$

half-width at half maximum = $(2\ln 2)^{1/2}\sigma = 1.177\sigma$

The cumulative distribution, Eq. (28.1), for a Gaussian with $\mu = 0$ and $\sigma^2 = 1$ is related to the error function erf(y) by

$$F(x; 0, 1) = \tfrac{1}{2}\left[1 + \mathrm{erf}(x/\sqrt{2})\right] \ . \tag{28.19}$$

The error function is tabulated in Ref. 6 and is available in computer math libraries and personel computer spreadsheets. For a mean μ and variance σ^2, replace x by $(x - \mu)/\sigma$. The probability of x in a given range can be calculated with Eq. (29.36).

For x and y independent and normally distributed, $z = ax + by$ obeys $f(z;\, a\mu_x + b\mu_y,\, a^2\sigma_x^2 + b^2\sigma_y^2)$; that is, the weighted means and variances add.

The Gaussian gets its importance in large part from the *central limit theorem*: If a continuous random variable x is distributed according to *any* p.d.f. with finite mean and variance, then the sample mean, $\overline{x}_n$, of n observations of x will have a p.d.f. that approaches a Gaussian as n increases. Therefore the end result $\sum^n x_i \equiv n\overline{x}_n$ of a large number of small fluctuations x_i will be distributed as a Gaussian, even if the x_i themselves are not.

For a set of n Gaussian random variables $\boldsymbol{x}$ with means $\boldsymbol{\mu}$ and corresponding Fourier variables $\boldsymbol{u}$, the characteristic function for a one-dimensional Gaussian is generalized to

$$\phi(\boldsymbol{x}; \boldsymbol{\mu}, S) = \exp\left[i\boldsymbol{\mu}\cdot\boldsymbol{u} - \tfrac{1}{2}\boldsymbol{u}^T S \boldsymbol{u}\right] \ . \tag{28.20}$$

From Eq. (28.13), the covariance about the mean is

$$E\left[(x_j - \mu_j)(x_k - \mu_k)\right] = S_{jk} \ . \tag{28.21}$$

If the $\boldsymbol{x}$ are independent, then $S_{jk} = \delta_{jk}\sigma_j^2$, and Eq. (28.20) is the product of the c.f.'s of n Gaussians.

The covariance matrix S can be related to the correlation matrix defined by Eq. (28.9) (a sort of normalized covariance matrix). With the definition $\sigma_k^2 \equiv S_{kk}$, we have $\rho_{jk} = S_{jk}/\sigma_j\sigma_k$.

The characteristic function may be inverted to find the corresponding p.d.f.

$$f(\boldsymbol{x}; \boldsymbol{\mu}, S) = \frac{1}{(2\pi)^{n/2}\sqrt{|S|}} \exp\left[-\tfrac{1}{2}(\boldsymbol{x} - \boldsymbol{\mu})^T S^{-1}(\boldsymbol{x} - \boldsymbol{\mu})\right] \tag{28.22}$$

where the determinant $|S|$ must be greater than 0. For diagonal S (independent variables), $f(\boldsymbol{x}; \boldsymbol{\mu}, S)$ is the product of the p.d.f.'s of n Gaussian distributions.

Table 28.1. Some common probability density functions, with corresponding characteristic functions and means and variances. In the Table, $\Gamma(k)$ is the gamma function, equal to $(k-1)!$ when k is an integer.

Distribution	Probability density function f (variable; parameters)	Characteristic function $\phi(u)$	Mean	Variance σ^2
Uniform	$f(x;a,b)=\begin{cases}1/(b-a) & a\le x\le b\\ 0 & \text{otherwise}\end{cases}$	$\dfrac{e^{ibu}-e^{iau}}{(b-a)iu}$	$\overline{x}=\dfrac{a+b}{2}$	$\dfrac{(b-a)^2}{12}$
Binomial	$f(r;n,p)=\dfrac{n!}{r!(n-r)!}\,p^r q^{n-r}$ $r=0,1,2,\dots,n\ ;\quad 0\le p\le 1\ ;\quad q=1-p$	$(q+pe^{iu})^n$	$\overline{r}=np$	npq
Poisson	$f(r;\mu)=\dfrac{\mu^r e^{-\mu}}{r!}\ ;\quad r=0,1,2,\dots\ ;\quad \mu>0$	$\exp[\mu(e^{iu}-1)]$	$\overline{r}=\mu$	μ
Normal (Gaussian)	$f(x;\mu,\sigma^2)=\dfrac{1}{\sigma\sqrt{2\pi}}\,\exp(-(x-\mu)^2/2\sigma^2)$ $-\infty<x<\infty\ ;\quad -\infty<\mu<\infty\ ;\quad \sigma>0$	$\exp(i\mu u-\frac{1}{2}\sigma^2u^2)$	$\overline{x}=\mu$	σ^2
Multivariate Gaussian	$f(\boldsymbol{x};\boldsymbol{\mu},S)=\dfrac{1}{(2\pi)^{n/2}\sqrt{\lvert S\rvert}}$ $\times\exp\left[-\frac{1}{2}(\boldsymbol{x}-\boldsymbol{\mu})^TS^{-1}(\boldsymbol{x}-\boldsymbol{\mu})\right]$ $-\infty<x_j<\infty;\quad -\infty<\mu_j<\infty;\quad \det S>0$	$\exp\left[i\boldsymbol{\mu}\cdot\boldsymbol{u}-\frac{1}{2}\boldsymbol{u}^TS\boldsymbol{u}\right]$	$\boldsymbol{\mu}$	S_{jk}
χ^2	$f(z;n)=\dfrac{z^{n/2-1}e^{-z/2}}{2^{n/2}\Gamma(n/2)}\ ;\quad z\ge 0$	$(1-2iu)^{-n/2}$	$\overline{z}=n$	$2n$
Student's t	$f(t;n)=\dfrac{1}{\sqrt{n\pi}}\,\dfrac{\Gamma[(n+1)/2]}{\Gamma(n/2)}\left(1+\dfrac{t^2}{n}\right)^{-(n+1)/2}$ $-\infty<t<\infty\ ;\quad n$ not required to be integer	—	$\overline{t}=0$ for $n\ge 2$	$n/(n-2)$ for $n\ge 3$
Gamma	$f(x;\lambda,k)=\dfrac{x^{k-1}\lambda^k e^{-\lambda x}}{\Gamma(k)}\ ;\quad 0<x<\infty\ ;$ k not required to be integer	$(1-iu/\lambda)^{-k}$	$\overline{x}=k/\lambda$	k/λ^2

For $n=2$, $f(\boldsymbol{x};\boldsymbol{\mu},S)$ is

$$f(x_1,x_2;\ \mu_1,\mu_2,\sigma_1,\sigma_2,\rho)=\frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}}$$
$$\times\ \exp\left\{\frac{-1}{2(1-\rho^2)}\left[\frac{(x_1-\mu_1)^2}{\sigma_1^2}-\frac{2\rho(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2}\right.\right.$$
$$\left.\left.+\frac{(x_2-\mu_2)^2}{\sigma_2^2}\right]\right\}\ . \tag{28.23}$$

The marginal distribution of any x_i is a Gaussian with mean μ_i and variance S_{ii}. S is $n\times n$, symmetric, and positive definite. Therefore for any vector $\boldsymbol{X}$, the quadratic form $\boldsymbol{X}^T S^{-1}\boldsymbol{X}=C$, where C is any positive number, traces an n-dimensional ellipsoid as $\boldsymbol{X}$ varies. If $X_i=(x_i-\mu_i)/\sigma_i$, then C is a random variable obeying the $\chi^2(n)$ distribution, discussed in the following section. The probability that $\boldsymbol{X}$ corresponding to a set of Gaussian random variables x_i lies *outside* the ellipsoid characterized by a given value of $C\ (=\chi^2)$ is given by Eq. (28.24) and may be read from Fig. 28.1. For example, the "s-standard-deviation ellipsoid" occurs at $C=s^2$. For the two-variable case ($n=2$), the point $\boldsymbol{X}$ lies outside the one-standard-deviation ellipsoid with 61% probability. (This assumes that μ_i and σ_i are correct.) For $X_i=x_i/\sigma_i$, the ellipsoids of constant χ^2 have the same size and orientation but are centered at $\boldsymbol{\mu}$. The use of these ellipsoids as indicators of probable error is described in Sec. 29.6.4.

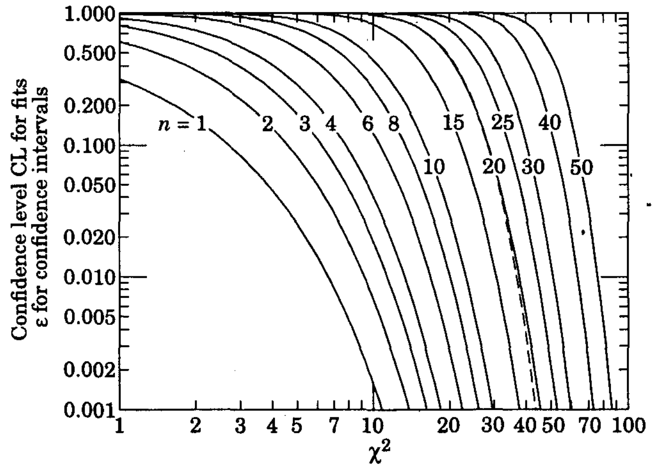

Figure 28.1: The confidence level versus χ^2 for n degrees of freedom, as defined in Eq. (28.24). The curve for a given n gives the probability that a value at least as large as χ^2 will be obtained in an experiment; *e.g.*, for $n=10$, a value $\chi^2\gtrsim 18$ will occur in 5% of a large number of experiments. For a fit, the CL is a measure of goodness-of-fit, in that a good fit to a correct model is expected to yield a low χ^2 (see Sec. 29.5.0). For a confidence interval, α measures the probability that the interval *does not* cover the true value of the quantity being estimated (see Sec. 29.6). The dashed curve for $n=20$ is calculated using the approximation of Eq. (28.25).

28.3.4. ***χ^2 distribution:*** If $x_1, \ldots, x_n$ are independent Gaussian distributed random variables, the sum $z = \sum^n (x_i - \mu_i)^2/\sigma_i^2$ is distributed as a χ^2 with n *degrees of freedom*, $\chi^2(n)$. Under a linear transformation to n dependent Gaussian variables x_i', the χ^2 at each transformed point retains its value; then $z = \boldsymbol{X}'^T\, V^{-1} \boldsymbol{X}'$ as in the previous section. For a set of z_i, each of which is $\chi^2(n_i)$, $\sum z_i$ is a new random variable which is $\chi^2\,(\sum n_i)$.

Fig. 28.1 shows the confidence level (CL) obtained by integrating the tail of $f(z;n)$:

$$\mathrm{CL}(\chi^2) = \int_{\chi^2}^{\infty} f(z;\, n)\, dz\ . \qquad (28.24)$$

This is shown for a special case in Fig. 28.2, and is equal to 1.0 minus the cumulative distribution function $F(z = \chi^2;\, n)$. It is useful in evaluating the consistency of data with a model (see Sec. 29): The CL is the probability that a random repeat of the given experiment would observe a greater χ^2, assuming the model is correct. It is also useful for confidence intervals for statistical estimators (see Sec. 29.6), in which case one is interested in the unshaded area of Fig. 28.2.

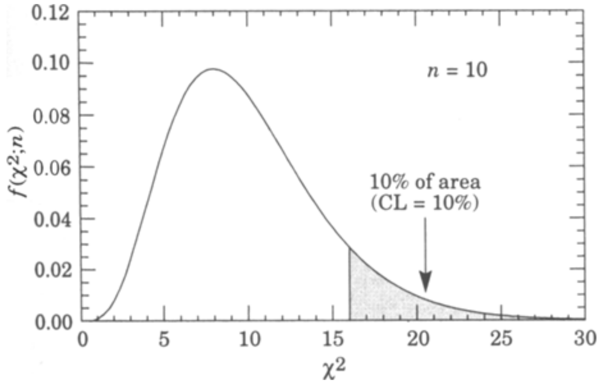

Figure 28.2: Illustration of the confidence level integral given in Eq. (28.24). This particular example is for $n = 10$, where the area above 15.99 is 0.1.

Since the mean of the χ^2 distribution is equal to n, one expects in a "reasonable" experiment to obtain $\chi^2 \approx n$. While caution is necessary because of the width and skewness of the distribution, the "reduced χ^2" $\equiv \chi^2/n$ is a sometimes useful quantity. Figure 28.3 shows χ^2/n for useful CL's as a function of n.

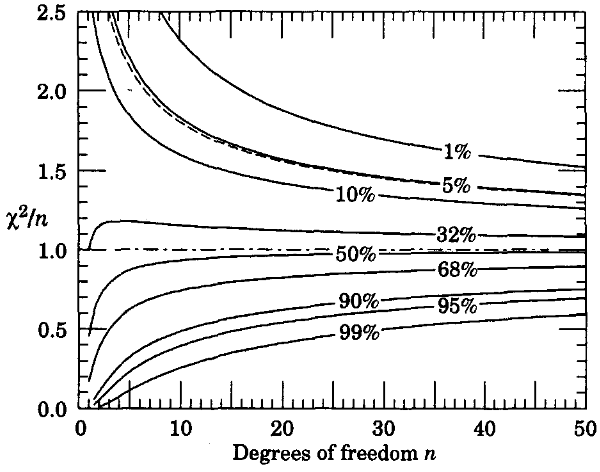

Figure 28.3: Confidence levels as a function of the "reduced χ^2" $\equiv \chi^2/n$ and the number of degrees of freedom n. Curves are labeled by the probability that a measurement will give a value of χ^2/n greater than that given on the y axis; *e.g.*, for $n = 10$, a value $\chi^2/n \gtrsim 1.8$ can be expected 5% of the time.

For large n, the CL is approximately given by [1,7]

$$\mathrm{CL}(\chi^2) \approx \frac{1}{\sqrt{2\pi}} \int_y^{\infty} e^{-x^2/2}\, dx\ , \qquad (28.25)$$

where $y = \sqrt{2\chi^2} - \sqrt{2n-1}$. This approximation was used to draw the dashed curves in Fig. 28.1 (for $n = 20$) and Fig. 28.3 (for CL = 5%). Since all the functions and their inverses are now readily available in standard mathematical libraries (such as IMSL, used to generate these figures, and personal computer spreadsheets, such as Microsoft®Excel [8]), the approximation (and even figures and tables) are seldom needed.

28.3.5. ***Student's t distribution:*** Suppose that x and $x_1, \ldots, x_n$ are independent and Gaussian distributed with mean 0 and variance 1. We then define

$$z = \sum_1^n x_i^2\ , \quad \text{and} \quad t = \frac{x}{\sqrt{z/n}}\ . \qquad (28.26)$$

The variable z thus belongs to a $\chi^2(n)$ distribution. Then t is distributed according to a Student's t distribution with n degrees of freedom, $f(t;n)$, given in Table 28.1.

The Student's t distribution resembles a Gaussian distribution with wide tails. As $n \to \infty$, the distribution approaches a Gaussian. If $n = 1$, the distribution is a *Cauchy* or *Breit-Wigner* distribution. The mean is finite only for $n > 1$ and the variance is finite only for $n > 2$, so for $n = 1$ or $n = 2$, t does not obey the central limit theorem.

As an example, consider the *sample mean* $\overline{x} = \sum x_i/n$ and the *sample variance* $s^2 = \sum(x_i - \overline{x})^2/(n-1)$ for normally distributed random variables x_i with unknown mean μ and variance σ^2. The sample mean has a Gaussian distribution with a variance σ^2/n, so the variable $(\overline{x} - \mu)/\sqrt{\sigma^2/n}$ is normal with mean 0 and variance 1. Similarly, $(n-1)\,s^2/\sigma^2$ is independent of this and is χ^2 distributed with $n - 1$ degrees of freedom. The ratio

$$t = \frac{(\overline{x} - \mu)/\sqrt{\sigma^2/n}}{\sqrt{(n-1)\,s^2/\sigma^2\,(n-1)}} = \frac{\overline{x} - \mu}{\sqrt{s^2/n}} \quad \cdot \qquad (28.27)$$

is distributed as $f(t;\, n-1)$. The unknown true variance σ^2 cancels, and t can be used to test the probability that the true mean is some particular value μ.

In Table 28.1, n in $f(t;n)$ is not required to be an integer. A Student's t distribution with nonintegral $n > 0$ is useful in certain applications.

28.3.6. ***Gamma distribution:*** For a process that generates events as a function of x (*e.g.*, space or time) according to a Poisson distribution, the distance in x from an arbitrary starting point (which may be some particular event) to the k^{th} event belongs to a *gamma* distribution, $f(x;\, \lambda,\, k)$. The Poisson parameter μ is λ per unit x. The special case $k = 1$ (*i.e.*, $f(x;\lambda,1) = \lambda e^{-\lambda x}$) is called the *exponential* distribution. A sum of k' exponential random variables x_i is distributed as $f(\sum x_i;\, \lambda, k')$.

The parameter k is not required to be an integer. For $\lambda = 1/2$ and $k = n/2$, the gamma distribution reduces to the $\chi^2(n)$ distribution.

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8. Microsoft® is a registered trademark of Microsoft corporation.

29. STATISTICS

Revised April 1998 by F. James (CERN).

29.1. Parameter estimation [1–4]

A probability density function $f(x;\alpha)$ with known parameters α enables us to predict the frequency with which random data x will take on a particular value (if discrete) or lie in a given range (if continuous). In *parametric* statistics we have the opposite problem of estimating the parameters α from a set of actual observations.

A *statistic* is any function of the data, plus known constants, which does not depend upon any of the unknown parameters. A statistic is a random variable if the data have random errors. An *estimator* is any statistic whose value (the *estimate* $\widehat{\alpha}$) is intended as a meaningful guess for the value of the parameter α, or the vector $\boldsymbol{\alpha}$ if there is more than one parameter.

Since we are free to choose any function of the data as an estimator of the parameter α, we will try to choose that estimator which has the best properties. The most important properties are (a) *consistency*, (b) *bias*, (c) *efficiency*, and (d) *robustness*.

(a) An estimator is said to be *consistent* if the estimate $\widehat{\alpha}$ converges to the true value α as the amount of data increases. This property is so important that it is possessed by all commonly used estimators.

(b) The *bias*, $b = E(\widehat{\alpha}) - \alpha$, is the difference between the true value and the expectation of the estimates, where the expectation value is taken over a hypothetical set of similar experiments in which $\widehat{\alpha}$ is constructed the same way. When $b = 0$ the estimator is said to be unbiased. The bias may be due to statistical properties of the estimator or to *systematic* errors in the experiment. If we can estimate the b we can subtract it from $\widehat{\alpha}$ to obtain a new $\widehat{\alpha}' \equiv \widehat{\alpha} - b$. However, b may depend upon α or other unknowns, in which case we usually try to choose an estimator which minimizes its average size.

(c) *Efficiency* is the inverse of the ratio between the *variance of the estimates* $\mathrm{Var}(\widehat{\alpha})$ and the minimum possible value of the variance. Under rather general conditions, the minimum variance is given by the Rao-Cramér-Frechet bound:

$$\mathrm{Var}_{\min} = \left[1 + \partial b/\partial\alpha\right]^2 / I(\alpha) \; ; \tag{29.1}$$

$$I(\alpha) = E\left\{ \left[\frac{\partial}{\partial\alpha} \sum_{i=1}^{n} \ln f(x_i;\alpha) \right]^2 \right\} .$$

(Compare with Eq. (29.6) below.) The sum is over all data and b is the bias, if any; the x_i are assumed independent and distributed as $f(x_i;\alpha)$, and the allowed range of x must not depend upon α. *Mean-squared error*, mse $= E[(\widehat{\alpha}-\alpha)^2] = V(\widehat{\alpha}) + b^2$ is a convenient quantity which combines in the appropriate way the errors due to bias and efficiency.

(d) *Robustness*; is the property of being insensitive to departures from assumptions in the p.d.f. due to such factors as noise.

For some common estimators the above properties are known exactly. More generally, it is always possible to evaluate them by Monte Carlo simulation. Note that they will often depend on the unknown α.

29.2. Data with a common mean

Suppose we have a set of N independent measurements y_i assumed to be unbiased measurements of the same unknown quantity μ with a common, but unknown, variance σ^2 resulting from measurement error. Then

$$\widehat{\mu} = \frac{1}{N} \sum_{i=1}^{N} y_i = E(y) \tag{29.2}$$

$$\widehat{\sigma}^2 = \frac{1}{N-1} \sum_{i=1}^{N} (y_i - \widehat{\mu})^2 = \frac{N}{N-1} \left(E(y^2) - \widehat{\mu}^2 \right) \tag{29.3}$$

are unbiased estimators of μ and σ^2. The variance of $\widehat{\mu}$ is σ^2/N. If the common p.d.f. of the y_i is Gaussian, these estimates are uncorrelated. Then, for large N, the standard deviation of $\widehat{\sigma}$ (the "error of the error") is $\sigma/\sqrt{2N}$. Again if the y_i are Gaussian, $\widehat{\mu}$ is an efficient estimator for μ. Otherwise the mean is in general not the most efficient estimator. For example, if the y follow a double-exponential distribution, the most efficient estimator of the mean is the sample median (the value for which half the y_i lie above and half below). This is discussed in more detail in Ref. 2, section 8.7.

If σ^2 is known, it does not improve the estimate $\widehat{\mu}$, as can be seen from Eq. (29.2); however, if μ is known, substitute it for $\widehat{\mu}$ in Eq. (29.3) and replace $N-1$ by N, to obtain a somewhat better estimator of σ^2.

If the y_i have different, known, variances σ_i^2, then the weighted average

$$\widehat{\mu} = \frac{1}{w} \sum^{N} w_i \, y_i \; , \tag{29.4}$$

is an unbiased estimator for μ with smaller variance than Eq. (29.2), where $w_i = 1/\sigma_i^2$ and $w = \sum w_i$. The standard deviation of $\widehat{\mu}$ is $1/\sqrt{w}$.

29.3. The method of maximum likelihood

29.3.1. *Parameter estimation by maximum likelihood*:

"From a theoretical point of view, the most important general method of estimation so far known is the *method of maximum likelihood*" [3]. We suppose that a set of independently measured quantities x_i came from a p.d.f. $f(x;\boldsymbol{\alpha})$, where $\boldsymbol{\alpha}$ is an unknown set of parameters. The method of maximum likelihood consists of finding the set of values, $\widehat{\boldsymbol{\alpha}}$, which maximizes the joint probability density for all the data, given by

$$\mathscr{L}(\boldsymbol{\alpha}) = \prod_i f(x_i;\boldsymbol{\alpha}) \; , \tag{29.5}$$

where $\mathscr{L}$ is called the likelihood. It is usually easier to work with $\ln\mathscr{L}$, and since both are maximized for the same set of $\boldsymbol{\alpha}$, it is sufficient to solve the *likelihood equation*

$$\frac{\partial \ln \mathscr{L}}{\partial \alpha_n} = 0 \; . \tag{29.6}$$

When the solution to Eq. (29.6) is a maximum, it is called the *maximum likelihood estimate* of $\boldsymbol{\alpha}$. The importance of the approach is shown by the following proposition, proved in Ref. 1:

> *If an efficient estimate $\widehat{\boldsymbol{\alpha}}$ of $\boldsymbol{\alpha}$ exists, the likelihood equation will have a unique solution equal to $\widehat{\boldsymbol{\alpha}}$.*

In evaluating $\mathscr{L}$, it is important that any normalization factors in the f's which involve $\boldsymbol{\alpha}$ be included. However, we will only be interested in the maximum of $\mathscr{L}$ and in ratios of $\mathscr{L}$ at different $\boldsymbol{\alpha}$'s; hence any multiplicative factors which do not involve the parameters we want to estimate may be dropped; this includes factors which depend on the data but not on $\boldsymbol{\alpha}$. The results of two or more independent experiments may be combined by forming the product of the $\mathscr{L}$'s, or the sum of the $\ln\mathscr{L}$'s.

Most commonly the solution to Eq. (29.6) will be found using a general numerical minimization program such as the CERN program MINUIT [8] which contains considerable code to take account of the many special cases and problems which can arise.

Under a one-to-one change of parameters from $\boldsymbol{\alpha}$ to $\boldsymbol{\beta} = \boldsymbol{\beta}(\boldsymbol{\alpha})$, the maximum likelihood estimate $\widehat{\boldsymbol{\alpha}}$ transforms to $\boldsymbol{\beta}(\widehat{\boldsymbol{\alpha}})$. That is, the maximum likelihood solution is invariant under change of parameter. However, many properties of $\widehat{\boldsymbol{\alpha}}$, in particular the bias, are not invariant under change of parameter.

29.3.2. *Confidence intervals from the likelihood function*:

The covariance matrix V may be estimated from

$$V_{nm} = \left(E\left[-\frac{\partial^2 \ln \mathcal{L}}{\partial\alpha_n\,\partial\alpha_m}\bigg|_{\widehat{\alpha}} \right] \right)^{-1} . \tag{29.7}$$

In the asymptotic case (or a linear model with Gaussian errors), $\mathcal{L}$ is Gaussian, $\ln\mathcal{L}$ is a (multidimensional) parabola, and the second derivative in Eq. (29.7) is constant, so the "expectation" operation has no effect. This leads to the usual approximation of calculating the error matrix of the parameters by inverting the second derivative matrix of $\ln\mathcal{L}$. In this asymptotic case, it can be seen that a numerically equivalent way of determining s-standard-deviation errors is from the contour given by the $\boldsymbol{\alpha}'$ such that

$$\ln\mathcal{L}(\boldsymbol{\alpha}') = \ln\mathcal{L}_{\rm max} - s^2/2 , \tag{29.8}$$

where $\ln\mathcal{L}_{\rm max}$ is the value of $\ln\mathcal{L}$ at the solution point (compare with Eq. (29.32), below). The extreme limits of this contour parallel to the α_n axis give an approximate s-standard-deviation confidence interval in α_n. These intervals may not be symmetric and in pathological cases they may even consist of two or more disjoint intervals.

Although asymptotically Eq. (29.7) is equivalent to Eq. (29.8) with $s = 1$, the latter is a better approximation when the model deviates from linearity. This is because Eq. (29.8) is invariant with respect to even a non-linear transformation of parameters $\boldsymbol{\alpha}$, whereas Eq. (29.7) is not. Still, when the model is non-linear or errors are not Gaussian, confidence intervals obtained with both these formulas are only approximate. The true coverage of these confidence intervals can always be determined by a Monte Carlo simulation, or exact confidence intervals can be determined as in Sec. 29.6.3.

29.3.3. *Application to Poisson-distributed data*:

In the case of Poisson-distributed data in a counting experiment, the unbinned maximum likelihood method (where the index i in Eq. (29.5) labels events) is preferred if the total number of events is very small. If there are enough events to justify binning them in a histogram, then one may alternatively maximize the likelihood function for the contents of the bins (so i labels bins). This is equivalent to minimizing [5]

$$\chi^2 = \sum_i \left[2(N_i^{\rm th} - N_i^{\rm obs}) + 2N_i^{\rm obs}\ln(N_i^{\rm obs}/N_i^{\rm th}) \right] . \tag{29.9}$$

where $N_i^{\rm obs}$ and $N_i^{\rm th}$ are the observed and theoretical (from f) contents of the ith bin. In bins where $N_i^{\rm obs} = 0$, the second term is zero. This function asymptotically behaves like a classical χ^2 for purposes of point estimation, interval estimation, *and goodness-of-fit*. It also guarantees that the area under the fitted function f is equal to the sum of the histogram contents (as long as the overall normalization of f is effectively left unconstrained during the fit), which is not the case for χ^2 statistics based on a least-squares procedure with traditional weights.

29.4. Propagation of errors

Suppose that $F(x;\boldsymbol{\alpha})$ is some function of variable(s) x and the fitted parameters $\boldsymbol{\alpha}$, with a value $\widehat{F}$ at $\widehat{\boldsymbol{\alpha}}$. The variance matrix of the parameters is V_{mn}. To first order in $\alpha_m - \widehat{\alpha}_m$, F is given by

$$F = \widehat{F} + \sum_m \frac{\partial F}{\partial\alpha_m}(\alpha_m - \widehat{\alpha}_m) , \tag{29.10}$$

and the variance of F about its estimator is given by

$$(\Delta F)^2 = E[(F - \widehat{F})^2] = \sum_{mn} \frac{\partial F}{\partial\alpha_m}\frac{\partial F}{\partial\alpha_n} V_{mn} , \tag{29.11}$$

evaluated at the x of interest. For different functions F_j and F_k, the covariance is

$$E[(F_j - \widehat{F}_j)(F_k - \widehat{F}_k)] = \sum_{mn} \frac{\partial F_j}{\partial\alpha_m}\frac{\partial F_k}{\partial\alpha_n} V_{mn} . \tag{29.12}$$

If the first-order approximation is in serious error, the above results may be very approximate. $\widehat{F}$ may be a biased estimator of F even if the $\widehat{\alpha}$ are unbiased estimators of $\boldsymbol{\alpha}$. Inclusion of higher-order terms or direct evaluation of F in the vicinity of $\widehat{\alpha}$ will help to reduce the bias.

29.5. Method of least squares

The *method of least squares* can be derived from the maximum likelihood theorem. We suppose a set of N measurements at points x_i. The ith measurement y_i is assumed to be chosen from a Gaussian distribution with mean $F(x_i;\boldsymbol{\alpha})$ and variance σ_i^2. Then

$$\chi^2 = -2\ln\mathcal{L} + \text{constant} = \sum_1^N \frac{[y_i - F(x_i;\boldsymbol{\alpha})]^2}{\sigma_i^2} . \tag{29.13}$$

Finding the set of parameters $\boldsymbol{\alpha}$ which maximizes $\mathcal{L}$ is the same as finding the set which minimizes χ^2.

In many practical cases one further restricts the problem to the situation in which $F(x_i;\boldsymbol{\alpha})$ is a linear function of the α_m's,

$$F(x_i;\boldsymbol{\alpha}) = \sum_n \alpha_n f_n(x) , \tag{29.14}$$

where the f_n are k linearly independent functions (*e.g.*, 1, x, x^2, ..., or Legendre polynomials) which are single-valued over the allowed range of x. We require $k \leq N$, and at least k of the x_i must be distinct. We wish to estimate the linear coefficients α_n. Later we will discuss the nonlinear case.

If the point errors $\epsilon_i = y_i - F(x_i;\boldsymbol{\alpha})$ are Gaussian, then the minimum χ^2 will be distributed as a χ^2 random variable with $n = N - k$ degrees of freedom. We can then evaluate the goodness-of-fit (confidence level) from Figs. 28.1 or 28.3, as per the earlier discussion. The confidence level expresses the probability that a *worse* fit would be obtained in a large number of similar experiments under the assumptions that: (a) the model $y = \sum \alpha_n f_n$ is correct and (b) the errors ϵ_i are Gaussian and unbiased with variance σ_i^2. If this probability is larger than an agreed-upon value (0.001, 0.01, or 0.05 are common choices), the data are *consistent* with the assumptions; otherwise we may want to find improved assumptions. As for the converse, most people do not regard a model as being truly *inconsistent* unless the probability is as low as that corresponding to four or five standard deviations for a Gaussian (6×10^{-3} or 6×10^{-5}; see Sec. 29.6.4). If the ϵ_i are not Gaussian, the method of least squares still gives an answer, but the goodness-of-fit test would have to be done using the correct distribution of the random variable which is still called "χ^2."

Finding the minimum of χ^2 in the linear case is straightforward:

$$\begin{aligned} -\frac{1}{2}\frac{\partial\chi^2}{\partial\alpha_m} &= \sum_i f_m(x_i)\left(\frac{y_i - \sum_n \alpha_n f_n(x_i)}{\sigma_i^2}\right) \\ &= \sum_i \frac{y_i\, f_m(x_i)}{\sigma_i^2} - \sum_n \alpha_n \sum_i \frac{f_n(x_i)\, f_m(x_i)}{\sigma_i^2} . \end{aligned} \tag{29.15}$$

With the definitions

$$g_m = \sum_i y_i\, f_m(x_i)/\sigma_i^2 \tag{29.16}$$

and

$$V_{mn}^{-1} = \sum_i f_n(x_i)\, f_m(x_i)/\sigma_i^2 , \tag{29.17}$$

the k-element column vector of solutions $\widehat{\alpha}$, for which $\partial\chi^2/\partial\alpha_m = 0$ for all m, is given by

$$\widehat{\boldsymbol{\alpha}} = V\,\boldsymbol{g} . \tag{29.18}$$

With this notation, χ^2 for the special case of a linear fitting function (Eq. (29.14)) can be rewritten in the compact form

$$\chi^2 = \chi^2_{\rm min} + (\boldsymbol{\alpha} - \widehat{\boldsymbol{\alpha}})^T V^{-1}(\boldsymbol{\alpha} - \widehat{\boldsymbol{\alpha}}) . \tag{29.19}$$

Nonindependent y_i's

Eq. (29.13) is based on the assumption that the likelihood function is the product of independent Gaussian distributions. More generally, the measured y_i's are not independent, and we must consider them as coming from a multivariate distribution with nondiagonal covariance matrix S, as described in Sec. 28.3.3. The generalization of Eq. (29.13) is

$$\chi^2 = \sum_{jk} [y_j - F(x_j;\boldsymbol{\alpha})] S^{-1}_{jk} [y_k - F(x_k;\boldsymbol{\alpha})] \ . \tag{29.20}$$

In the case of a fitting function that is linear in the parameters, one may differentiate χ^2 to find the generalization of Eq. (29.15), and with the extended definitions

$$\begin{aligned} g_m &= \sum_{jk} y_j \ f_m(x_k) S^{-1}_{jk} \\ V^{-1}_{mn} &= \sum_{jk} f_n(x_j) \ f_m(x_k) S^{-1}_{jk} \end{aligned} \tag{29.21}$$

solve Eq. (29.18) for the estimators $\widehat{\boldsymbol{\alpha}}$.

The problem of constructing the covariance matrix S is simplified by the fact that contributions to S (not to its inverse) are additive. For example, suppose that we have three variables, all of which have independent statistical errors. The first two also have a common error resulting in a positive correlation, perhaps because a common baseline with its own statistical error (variance s^2) was subtracted from each. In addition, the second two have a common error (variance a^2), but this time the values are anticorrelated. This might happen, for example, if the sum of the two variables is a constant. Then

$$\begin{aligned} S = &\begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix} \\ &+ \begin{pmatrix} s^2 & s^2 & 0 \\ s^2 & s^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & a^2 & -a^2 \\ 0 & -a^2 & a^2 \end{pmatrix} \ . \end{aligned} \tag{29.22}$$

If unequal amounts of the common baseline were subtracted from variables 1, 2, and 3—*e.g.*, fractions f_1, f_2, and f_3, then we would have

$$\begin{aligned} S = &\begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix} \\ &+ \begin{pmatrix} f_1^2 s^2 & f_1 f_2 s^2 & f_1 f_3 s^2 \\ f_1 f_2 s^2 & f_2^2 s^2 & f_2 f_3 s^2 \\ f_1 f_3 s^2 & f_2 f_3 s^2 & f_3^2 s^2 \end{pmatrix} \ . \end{aligned} \tag{29.23}$$

While in general this "two-vector" representation is not possible, it underscores the procedure: Add zero-determinant correlation matrices to the matrix expressing the independent variation.

Care must be taken when fitting to correlated data, since off-diagonal contributions to χ^2 are not necessarily positive. It is even possible for all of the residuals to have the same sign.

Example: straight-line fit

For the case of a straight-line fit, $y(x) = \alpha_1 + \alpha_2\, x$, one obtains, for independent measurements y_i, the following estimates of α_1 and α_2,

$$\widehat{\alpha}_1 = (g_1\, \Lambda_{22} - g_2\, \Lambda_{12})/D \ , \tag{29.24}$$

$$\widehat{\alpha}_2 = (g_2\, \Lambda_{11} - g_1\, \Lambda_{12})/D \ , \tag{29.25}$$

where

$$(\Lambda_{11}, \Lambda_{12}, \Lambda_{22}) = \sum (1, x_i, x_i^2)/\sigma_i^2 \ , \tag{29.26a}$$

$$(g_1, g_2) = \sum (1, x_i) y_i/\sigma_i^2 \ . \tag{29.26b}$$

respectively, and

$$D = \Lambda_{11}\, \Lambda_{22} - (\Lambda_{12})^2 \ . \tag{29.27}$$

The covariance matrix of the fitted parameters is:

$$\begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix} = \frac{1}{D} \begin{pmatrix} \Lambda_{22} & -\Lambda_{12} \\ -\Lambda_{12} & \Lambda_{11} \end{pmatrix} \ . \tag{29.28}$$

The estimated variance of an interpolated or extrapolated value of y at point x is:

$$(\widehat{y} - y_{\text{true}})^2 \Big|_{\text{est}} = \frac{1}{\Lambda_{11}} + \frac{\Lambda_{11}}{D} \left(x - \frac{\Lambda_{12}}{\Lambda_{11}} \right)^2 \ . \tag{29.29}$$

29.5.1. *Confidence intervals from the chisquare function*:

If y is not linear in the fitting parameters $\boldsymbol{\alpha}$, the solution vector may have to be found by iteration. If we have a first guess $\boldsymbol{\alpha}_0$, then we may expand to obtain

$$\left.\frac{\partial\chi^2}{\partial\boldsymbol{\alpha}}\right|_{\boldsymbol{\alpha}} = \left.\frac{\partial\chi^2}{\partial\boldsymbol{\alpha}}\right|_{\boldsymbol{\alpha}_0} + V^{-1}_{\boldsymbol{\alpha}_0} \cdot (\boldsymbol{\alpha} - \boldsymbol{\alpha}_0) + \ldots \ , \tag{29.30}$$

where $\partial\chi^2/\partial\boldsymbol{\alpha}$ is a vector whose mth component is $\partial\chi^2/\partial\alpha_m$, and $(V^{-1}_{mn}) = \frac{1}{2}\partial^2\chi^2/\partial\alpha_m\partial\alpha_n$. (See Eqns. 29.7 and 29.17. When evaluated at $\widehat{\boldsymbol{\alpha}}$, V^{-1} is the inverse of the covariance matrix.) The next iteration toward $\widehat{\boldsymbol{\alpha}}$ can be obtained by setting $\partial\chi^2/\partial\alpha_m|_{\boldsymbol{\alpha}} = 0$ and neglecting higher-order terms:

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}_0 - V_{\boldsymbol{\alpha}_0} \cdot \partial\chi^2/\partial\boldsymbol{\alpha}|_{\boldsymbol{\alpha}_0} \ . \tag{29.31}$$

If V is constant in the vicinity of the minimum, as it is when the model function is linear in the parameters, then χ^2 is parabolic as a function of $\boldsymbol{\alpha}$ and Eq. (29.31) gives the solution immediately. Otherwise, further iteration is necessary. If the problem is highly nonlinear, considerable difficulty may be encountered. There may be secondary minima, and χ^2 may be decreasing at physical boundaries. Numerical methods have been devised to find such solutions without divergence [7,8]. In particular, the CERN program MINUIT [8] offers several iteration schemes for solving such problems.

Note that minimizing any function proportional to χ^2 (or maximizing any function proportional $\ln\mathscr{L}$) will result in the same parameter set $\widehat{\boldsymbol{\alpha}}$. Hence, for example, if the variances σ_j^2 are known only up to a common constant, one can still solve for $\widehat{\boldsymbol{\alpha}}$. One cannot, however, evaluate goodness-of-fit, and the covariance matrix is known only to within the constant multiplier. The scale can be estimated at least roughly from the value of χ^2 compared to its expected value.

Additional information can be extracted from the behavior of the (normalized) residuals, $r_j = (y_j - F(x_j;\boldsymbol{\alpha})/\sigma_j$, which should themselves distribute normally with a mean of 0.

If the data covariance matrix S has been correctly evaluated (or, equivalently, the σ_j's, if the data are independent), then the s-standard deviation limits on the parameters are given by a set $\boldsymbol{\alpha}'$ such that

$$\chi^2(\boldsymbol{\alpha}') = \chi^2_{\min} + s^2 \ . \tag{29.32}$$

This equation gives confidence intervals in the same sense as 29.8, and all the discussion of Sec. 29.3.2 applies as well here, substituting $-\chi^2/2$ for $\ln\mathscr{L}$.

29.6. Exact confidence intervals

29.6.1. *Two methodologies*:

There are two different approaches to statistical inference, which we may call Frequentist and Bayesian. For the cases considered up to now, both approaches give the same numerical answers, even though they are based on fundamentally different assumptions. However, for exact results for small samples and for measurements near a physical boundary, the different approaches may yield very different confidence limits, so we are forced to make a choice. There is an enormous amount of literature devoted to the question of Bayesian vs non-Bayesian methods, most of it written by people who are fervent advocates of one or the other methodology, which often leads to exaggerated conclusions. For a reasonably balanced discussion, we recommend the following articles: by a statistician [9], and by a physicist [6].

29.6.2. ***Bayesian***: The Bayesian concept of probability is not based on limiting frequencies, but is more general and includes *degrees of belief*. It can therefore be used for experiments which cannot be repeated, where a frequency definition of probability would not be applicable (for example, one can consider the probability that it will rain tomorrow). Bayesian methods also allow for a natural way to input additional information such as physical boundaries and subjective information; in fact they *require* as input the *prior distribution* for any parameter to be estimated.

The Bayesian methodology, while well adapted to decision-making situations, is not in general appropriate for the objective presentation of experimental data. This can be seen from the following example.

An experiment sets out to measure the value of a parameter whose true value cannot be negative (such as the neutrino mass squared), but let us assume that the true value is in fact zero. We should then expect that about half of the time, an unbiased experimental measurement should yield a negative (unphysical) result. Now if our experiment produces a negative result, the question arises what value to report. If we wish to make a decision concerning the most likely value of this parameter, we would use a Bayesian approach which would assure that the reported value is positive, since it would be nonsense to assert that the most likely value is one which cannot be true. On the other hand, if we wish to report an unbiased result which can be combined with other measurements, it is better to report the unphysical result. Everyone understands what it means to quote a result of, for example, $m^2 = -1.2 \pm 2.0$ eV^2. This result could then be averaged with other results, half of which would be positive, and the average would eventually converge toward zero, the true value. If Bayesian estimates are averaged, they do not converge to the true value, since they have all been forced to be positive.

29.6.3. ***Frequentist, or classical confidence intervals***: As the name implies, the Frequentist concept of probability is based entirely on the limiting frequency, so it only makes sense in situations where experiments are repeatable, at least in principle. This is clearly the case for the kind of data we are concerned with, and the methods we present here are based on the Frequentist point of view.

The classical construction of exact confidence intervals which we describe here was first proposed by Neyman [10].

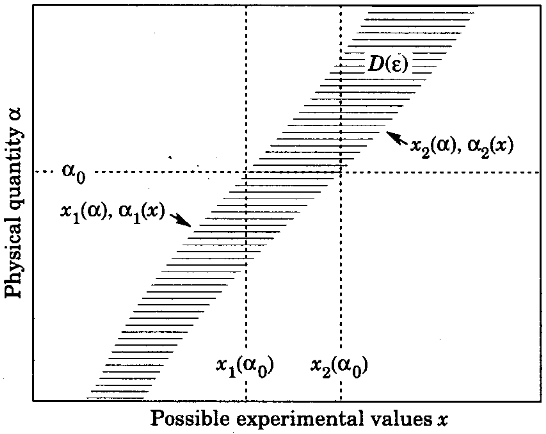

Figure 29.1: Confidence intervals for a single unknown parameter α. One might think of the p.d.f. $f(x;\alpha)$ as being plotted out of the paper as a function of x along each horizontal line of constant α. The domain $D(\varepsilon)$ contains a fraction $1-\varepsilon$ of the area under each of these functions.

We wish to set limits on the parameter α whose true value is fixed but unknown. The properties of our experimental apparatus are expressed in the function $f(x;\alpha)$ which gives the probability of observing data x if the true value of the parameter is α. This function must be known, otherwise it is impossible to interpret the results of an experiment. For a large complex experiment, this function is usually determined numerically using Monte Carlo simulation.

Given the function $f(x;\alpha)$, we can find for every value of α, two values $x_1(\alpha,\varepsilon)$ and $x_2(\alpha,\varepsilon)$ such that repeated experiments would produce results x in the interval $x_1 < x < x_2$ a fraction $1-\varepsilon$ of the time, where

$$P(x_1 < x < x_2) \; = \; 1-\varepsilon \; = \; \int_{x_1}^{x_2} f(x;\alpha)\, dx \; . \qquad (29.33)$$

This situation is shown in Fig. 29.1, where the region between the curves $x_1(\alpha,\varepsilon)$ and $x_2(\alpha,\varepsilon)$ is indicated by the domain $D(\varepsilon)$. We require that the curves $x_1(\alpha,\varepsilon)$ and $x_2(\alpha,\varepsilon)$ be monotonic functions of α, so they can be labeled either as functions of x or of α. Dropping the argument ε for simplicity, we may then label the curve $x_1(\alpha)$ as $\alpha_1(x)$ and $x_2(\alpha)$ as $\alpha_2(x)$. Now consider some arbitrary particular value of α, say α_0, as indicated in the figure. We notice from the figure that for all values of x between $x_1(\alpha_0)$ and $x_2(\alpha_0)$, it happens that α_0 lies between $\alpha_1(x)$ and $\alpha_2(x)$. Thus we can write:

$$P[x_1(\alpha_0) < x < x_2(\alpha_0)] \; = \; 1-\varepsilon \; = \; P[\alpha_2(x) < \alpha_0 < \alpha_1(x)] \, . \qquad (29.34)$$

And since, by construction, this is true for any value α_0, we can drop the subscript 0 and obtain the relationship we wanted to establish for the probability that the confidence limits will contain the true value of α:

$$P[\alpha_2(x) < \alpha < \alpha_1(x)] \; = \; 1-\varepsilon \; . \qquad (29.35)$$

In this probability statement, α_1 and α_2 are the random variables (not α), and we can verify that the statement is true, as a limiting ratio of frequencies in random experiments, for any assumed value of α. In a particular real experiment, the numerical values α_1 and α_2 are determined by applying the algorithm to the real data, and the probability statement appears to be a statement about the true value α since this is the only unknown remaining in the equation. It should however be understood that it gives only the probability of obtaining values α_1 and α_2 which include the true value of α, in an ensemble of identical experiments. Any method which gives confidence intervals that contain the true value with probability $1-\varepsilon$ (no matter what the true value of α is) is said to have *coverage*. The frequentist intervals as constructed above have *coverage* by construction. Coverage is considered the most important property of confidence intervals [6].

The condition of coverage Eq. (29.33) does not determine x_1 and x_2 completely, since any range which gives the desired value of the integral would give the same coverage. Additional criteria are needed to determine the intervals uniquely. The most common criterion is to choose *central intervals* such that the area of the excluded tail on either side is $\varepsilon/2$. This criterion is sufficient in most cases, but there is a more general *ordering principle* which reduces to centrality in the usual cases and produces confidence intervals with better properties when in the neighborhood of a physical limit. This ordering principle, which consists of taking the interval which includes the largest values of a likelihood ratio, is described by Feldman and Cousins [11].

29.6.4. ***Gaussian errors***:

If the data are such that the distribution of the estimator(s) satisfies the central limit theorem discussed in Sec. 28.3.3, the function $f(x;\alpha)$ is the Gaussian distribution. If there is more than one parameter being estimated, the multivariate Gaussian is used. For the univariate case with known σ,

$$1-\varepsilon = \int_{\mu-\delta}^{\mu+\delta} e^{\dfrac{-(x-\mu)^2}{2\sigma^2}}\, dx = \operatorname{erf}\left(\frac{\delta}{\sqrt{2}\,\sigma}\right) \qquad (29.36)$$

is the probability that the measured value x will fall within $\pm\delta$ of the true value μ. From the symmetry of the Gaussian with respect to x and μ, this is also the probability that the true value will be within $\pm\delta$ of the measured value. Fig. 29.2 shows a $\delta = 1.64\sigma$ confidence interval unshaded. The choice $\delta = \sqrt{\mathrm{Var}(\mu)} \equiv \sigma$ gives an interval called the ***standard error*** which has $1-\varepsilon = 68.27\%$ if σ is known. Confidence coefficients ε for other frequently used choices of δ are given in Table 29.1. For other δ, find ε as the ordinate of Fig. 28.1 on the $n=1$ curve at $\chi^2 = (\delta/\sigma)^2$. We can set a one-sided (upper or lower) limit by excluding above $\mu+\delta$ (or below $\mu-\delta$); ε's for such limits are 1/2 the values in Table 29.1.

For multivariate α the scalar $\mathrm{Var}(\mu)$ becomes a full variance-covariance matrix. Assuming a multivariate Gaussian, Eq. (28.22), and subsequent discussion the standard error ellipse for the pair $(\widehat{\alpha}_m, \widehat{\alpha}_n)$ may be drawn as in Fig. 29.3.

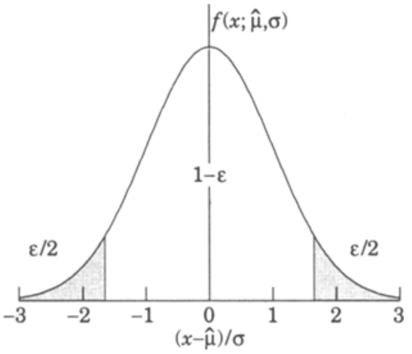

Figure 29.2: Illustration of a symmetric 90% confidence interval (unshaded) for a measurement of a single quantity with Gaussian errors. Integrated probabilities, defined by ε, are as shown.

Table 29.1: Area of the tails ε outside $\pm\delta$ from the mean of a Gaussian distribution.

ε (%)	δ	ε (%)	δ
31.73	1σ	20	1.28σ
4.55	2σ	10	1.64σ
0.27	3σ	5	1.96σ
6.3×10^{-3}	4σ	1	2.58σ
5.7×10^{-5}	5σ	0.1	3.29σ
2.0×10^{-7}	6σ	0.01	3.89σ

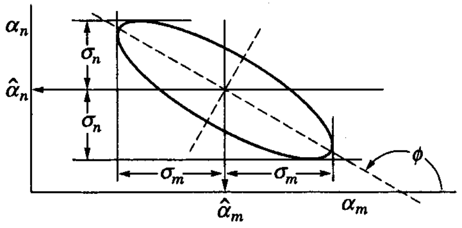

Figure 29.3: Standard error ellipse for the estimators $\hat{\alpha}_m$ and $\hat{\alpha}_n$. In this case the correlation is negative.

The minimum χ^2 or maximum likelihood solution is at $(\hat{\alpha}_m, \hat{\alpha}_n)$. The standard errors σ_m and σ_n are defined as shown, where the ellipse is at a constant value of $\chi^2 = \chi^2_{\rm min} + 1$ or $\ln \mathscr{L} = \ln \mathscr{L}_{\rm max} - 1/2$. The angle of the major axis of the ellipse is given by

$$\tan 2\phi = \frac{2\rho_{mn}\,\sigma_m\,\sigma_n}{\sigma_m^2 - \sigma_n^2} \; . \tag{29.37}$$

For non-Gaussian or nonlinear cases, one may construct an analogous contour from the same χ^2 or $\ln \mathscr{L}$ relations. Any other parameters $\hat{\alpha}_\ell, \ell \neq m, n$ must be allowed freely to find their optimum values for every trial point.

For any unbiased procedure (*e.g.*, least squares or maximum likelihood) being used to estimate k parameters α_i, $i = 1, \ldots, k$, the probability $1 - \varepsilon$ that the true values of all k lie within the s-standard deviation ellipsoid may be found from Fig. 28.1. Read the ordinate as ε; the correct value of ε occurs on the $n = k$ curve at $\chi^2 = s^2$. For example, for $k = 2$, the probability that the true values of α_1 and α_2 simultaneously lie within the one-standard-deviation error ellipse ($s = 1$), centered on $\hat{\alpha}_1$ and $\hat{\alpha}_2$, is 39%. This probability only assumes Gaussian errors, unbiased estimators, and that the model describing the data in terms of the α_i is correct.

29.6.5. *Upper limits and two-sided intervals*:

When a measured value is close to a physical boundary, it is natural to report a one-sided confidence interval (usually an upper limit). It is straightforward to force the procedure of Sec. 29.6.3 to produce only an upper limit, by setting $x_2 = \infty$ in Eq. (29.33). Then x_1 is uniquely determined. Clearly this procedure will have the desired coverage, but *only if we always choose to set an upper limit.* In practice one might decide after seeing the data whether to set an upper limit or a two-sided limit. In this case the upper limits calculated by Eq. (29.33) will not give exact coverage, as has been noted in Ref. 11.

In order to correct this problem and assure coverage in all circumstances, it is necessary to adopt a *unified procedure*, that is, a single ordering principle which will provide coverage globally. Then it is the *ordering principle* which decides whether a one-sided or two-sided interval will be reported for any given set of data. The appropriate unified procedure and ordering principle are given in Ref. 11. We reproduce below the main results.

29.6.6. *Gaussian data close to a boundary*:

One of the most controversial statistical questions in physics is how to report a measurement which is close to the edge or even outside of the allowed physical region. This is because there are several admissible possibilities depending on how the result is to be used or interpreted. Normally one or more of the following should be reported:

(a) In any case, the actual measurement should be reported, even if it is outside the physical region. As with any other measurement, it is best to report the value of a quantity which is nearly Gaussian distributed if possible. Thus one may choose to report mass squared rather than mass, or $\cos\theta$ rather than θ. For a complex quantity z close to zero, report $Re(z)$ and $Im(z)$ rather than amplitude and phase of z. Data carefully reported in this way can be unbiased, objective, easily interpreted and combined (averaged) with other data in a straightforward way, even if it lies partly or wholly outside the physical region. The reported error is a direct measure of the intrinsic accuracy of the result, which cannot always be inferred from the upper limits proposed below.

(b) If the data are to be used to make a decision, for example to determine the dimensions of a new experimental apparatus for an improved measurement, it may be appropriate to report a Bayesian upper limit, which must necessarily contain subjective feelings about the possible values of the parameter, as well as containing information about the physical boundary. Its interpretation requires knowledge of the prior distribution which was necessarily used to obtain it.

(c) If it is desired to report an upper limit in an objective way such that it has a well-defined statistical meaning in terms of a limiting frequency, then report the Frequentist confidence bound(s) as given by the unified Feldman-Cousins approach. This algorithm always gives a non-null interval (that is, the confidence limits are always inside the physical region, even for a measurement well outside the physical region), and still has correct global coverage. These confidence limits for a Gaussian measurement close to a non-physical boundary are summarized in Fig. 29.4. Additional tables are given in Ref. 11.

29.6.7. *Poisson data for small samples*:

When the observable is restricted to integer values (as in the case of Poisson and binomial distributions), it is not generally possible to construct confidence intervals with exact coverage for all values of α. In these cases the integral in Eq. (29.33) becomes a sum of finite contributions and it is no longer possible (in general) to find consecutive terms which add up exactly to the required confidence level $1 - \varepsilon$ for all values of α. Thus one constructs intervals which happen to have exact coverage for a few values of α, and unavoidable over-coverage for all other values. This is the best that can be done and still guarantee coverage for any true value.

In addition to the problem posed by the discreteness of the data, we usually have to contend with possible background whose expectation must be evaluated separately and may not be known precisely. For these reasons, the reporting of this kind of data is even more controversial than the Gaussian data near a boundary as discussed above. This is especially true when the number of observed counts is

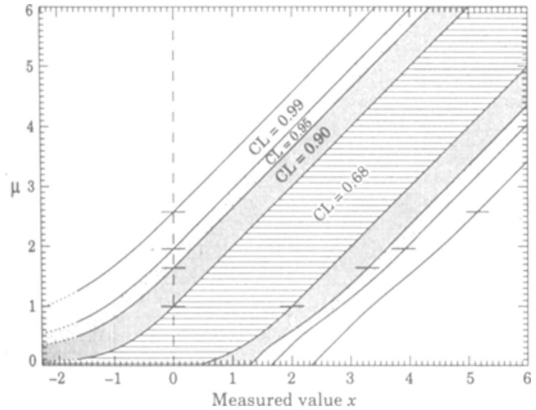

Figure 29.4: Plot of 99%, 95%, 90%, and 68.27% ("one σ") confidence intervals for a physical quantity μ based on a Gaussian measurement x (in units of standard deviations), for the case where the true value of μ cannot be negative. The curves become straight lines above the horizontal tick marks. The probability of obtaining an experimental value at least as negative as the left edge of the graph ($x = -2.33$) is less than 1%. Values of x more negative than -1.64 (dotted segments) are less than 5% probable, no matter what the true value of μ.

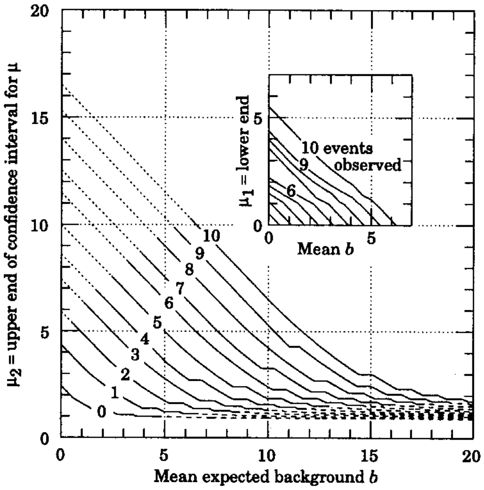

Figure 29.5: 90% confidence intervals $[\mu_1, \mu_2]$on the number of signal events as a function of the expected number of background events b. For example, if the expected background is 8 events and 5 events are observed, then the signal is 2.60 or less with 90% confidence. Dotted portions of the μ_2 curves on the upper left indicate regions where μ_1 is non-zero (as shown by the inset). Dashed portions in the lower right indicate regions where the probability of obtaining the number of events observed or fewer is less than 1%, even if $\mu = 0$. Horizontal curve sections occur because of discrete number statistics. Tables showing these data as well as the CL = 68.27%, 95%, and 99% results are given in Ref. 11.

greater than the expected background. As for the Gaussian case, there are at least three possibilities for reporting such results depending on how the result is to be used:

(a) In any case, the actual measurements should be reported, which means (1) the number of recorded counts, (2) the expected background, possibly with its error, and (3) normalization factor which turns the number of counts into a cross section, decay rate, etc. As with Gaussian data, this data can be combined with that of other experiments, to make improved upper limits for example.

(b) A Bayesian upper limit may be reported. This has the advantages and disadvantages of any Bayesian result as discussed above. It is especially difficult to find an acceptable prior probability distribution for this case.

Table 29.2: Poisson limits $[\mu_1, \mu_2]$ for n_0 observed events in the absence of background.

	CI = 90%		CI = 95%	
n_0	μ_1	μ_2	μ_1	μ_2
0	0.00	2.44	0.00	3.09
1	0.11	4.36	0.05	5.14
2	0.53	5.91	0.36	6.72
3	1.10	7.42	0.82	8.25
4	1.47	8.60	1.37	9.76
5	1.84	9.99	1.84	11.26
6	2.21	11.47	2.21	12.75
7	3.56	12.53	2.58	13.81
8	3.96	13.99	2.94	15.29
9	4.36	15.30	4.36	16.77
10	5.50	16.50	4.75	17.82

(c) An upper limit (or confidence region) with optimal coverage can be reported using the unified approach of Ref. 11. At the moment these confidence limits have been calculated only for the case of exactly known background expectation. The main results can be read from Fig. 29.5 or from Table 29.2; more extensive tables can be found in Ref. 11.

None of the above gives a single number which quantifies the quality or sensitivity of the experiment. This is a serious shortcoming of most upper limits including those of method (c), since it is impossible to distinguish, from the upper limit alone, between a clean experiment with no background and a lucky experiment with fewer observed counts than expected background. For this reason, we suggest that in addition to (a) and (c) above, a measure of the sensitivity should be reported whenever expected background is larger or comparable to the number of observed counts. The best such measure we know of is that proposed and tabulated in Ref. 11, defined as the average upper limit that would be attained by an ensemble of experiments with the expected background and no true signal.

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30. MONTE CARLO TECHNIQUES

Revised July 1995 by S. Youssef (SCRI, Florida State University).

Monte Carlo techniques are often the only practical way to evaluate difficult integrals or to sample random variables governed by complicated probability density functions. Here we describe an assortment of methods for sampling some commonly occurring probability density functions.

30.1. Sampling the uniform distribution

Most Monte Carlo sampling or integration techniques assume a "random number generator" which generates uniform statistically independent values on the half open interval $[0,1)$. Although such a generator is, strictly speaking, impossible on a finite digital computer, generators are nevertheless available which pass extensive batteries of tests for statistical independence and which have periods which are so long that, for practical purposes, values from these generators can be considered to be uniform and statistically independent. In particular, the lagged-Fibonacci based generator introduced by Marsaglia, Zaman, and Tsang [1] is efficient, has a period of approximately 10^{43}, produces identical sequences on a wide variety of computers and, passes the extensive "DIEHARD" battery of tests [2]. Many commonly available congruential generators fail these tests and often have sequences (typically with periods less than 2^{32}) which can be easily exhausted on modern computers and should therefore be avoided [3].

30.2. Inverse transform method

If the desired probability density function is $f(x)$ on the range $-\infty < x < \infty$, its cumulative distribution function (expressing the probability that $x \leq a$) is given by Eq. (28.1). If a is chosen with probability density $f(a)$, then the integrated probability up to point a, $F(a)$, is itself a random variable which will occur with uniform probability density on $[0,1]$. If x can take on any value, and ignoring the endpoints, we can then find a unique x chosen from the p.d.f. $f(s)$ for a given u if we set

$$u = F(x) \ , \tag{30.1}$$

provided we can find an inverse of F, defined by

$$x = F^{-1}(u) \ . \tag{30.2}$$

This method is shown in Fig. 30.1a.

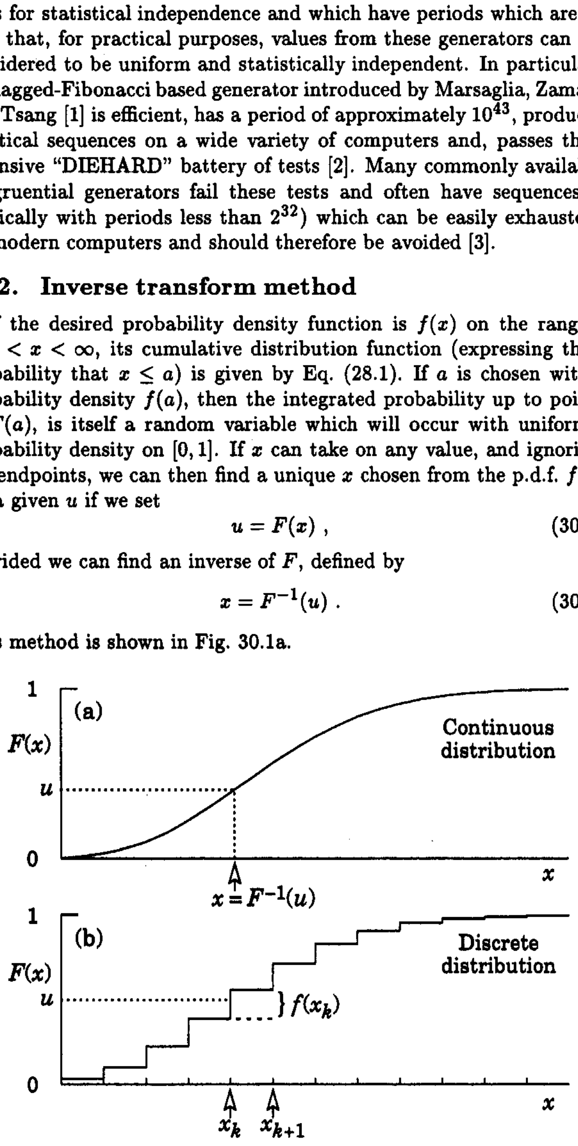

Figure 30.1: Use of a random number u chosen from a uniform distribution (0,1) to find a random number x from a distribution with cumulative distribution function $F(x)$.

For a discrete distribution, $F(x)$ will have a discontinuous jump of size $f(x_k)$ at each allowed $x_k, k = 1, 2, \cdots$. Choose u from a uniform distribution on (0,1) as before. Find x_k such that

$$F(x_{k-1}) < u \leq F(x_k) \equiv \text{Prob}\ (x \leq x_k) = \sum_{i=1}^{k} f(x_i) \ ; \tag{30.3}$$

then x_k is the value we seek (note: $F(x_0) \equiv 0$). This algorithm is illustrated in Fig. 30.1b.

30.3. Acceptance-rejection method (Von Neumann)

Very commonly an analytic form for $F(x)$ is unknown or too complex to work with, so that obtaining an inverse as in Eq. (30.2) is impractical. We suppose that for any given value of x the probability density function $f(x)$ can be computed and further that enough is known about $f(x)$ that we can enclose it entirely inside a shape which is C times an easily generated distribution $h(x)$ as illustrated in Fig. 30.2.

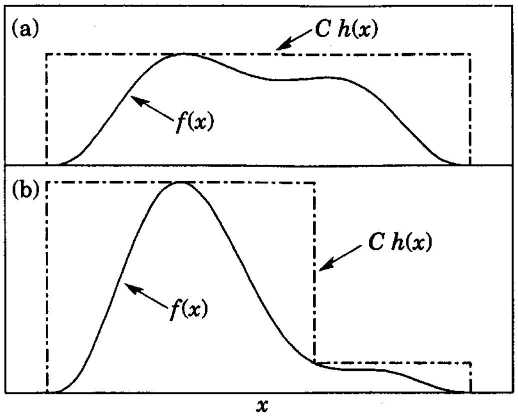

Figure 30.2: Illustration of the acceptance-rejection method. Random points are chosen inside the upper bounding figure, and rejected if the ordinate exceeds $f(x)$. Lower figure illustrates importance sampling.

Frequently $h(x)$ is uniform or is a normalized sum of uniform distributions. Note that both $f(x)$ and $h(x)$ must be normalized to unit area and therefore the proportionality constant $C > 1$. To generate $f(x)$, first generate a candidate x according to $h(x)$. Calculate $f(x)$ and the height of the envelope $C\,h(x)$; generate u and test if $uC\,h(x) \leq f(x)$. If so, accept x; if not reject x and try again. If we regard x and $uC\,h(x)$ as the abscissa and ordinate of a point in a two-dimensional plot, these points will populate the entire area $C\,h(x)$ in a smooth manner; then we accept those which fall under $f(x)$. The efficiency is the ratio of areas, which must equal $1/C$; therefore we must keep C as close as possible to 1.0. Therefore we try to choose $C\,h(x)$ to be as close to $f(x)$ as convenience dictates, as in the lower part of Fig. 30.2. This practice is called importance sampling, because we generate more trial values of x in the region where $f(x)$ is most important.

30.4. Algorithms

Algorithms for generating random numbers belonging to many different distributions are given by Press [4], Ahrens and Dieter [5], Rubinstein [6], Everett and Cashwell [7], Devroye [8], and Walck [9]. For many distributions alternative algorithms exist, varying in complexity, speed, and accuracy. For time-critical applications, these algorithms may be coded in-line to remove the significant overhead often encountered in making function calls. Variables named "u" are assumed to be independent and uniform on (0,1).

In the examples given below, we use the notation for the variables and parameters given in Table 28.1.

30.4.1. *Sine and cosine of random angle*:

Generate u_1 and u_2. Then $v_1 = 2u_1 - 1$ is uniform on $(-1,1)$, and $v_2 = u_2$ is uniform on (0,1). Calculate $r^2 = v_1^2 + v_2^2$. If $r^2 > 1$, start over. Otherwise, the sine (S) and cosine (C) of a random angle are given by

$$S = 2v_1v_2/r^2 \quad \text{and} \quad C = (v_1^2 - v_2^2)/r^2 \ . \tag{30.4}$$

30.4.2. *Gaussian distribution*:

If u_1 and u_2 are uniform on (0,1), then

$$z_1 = \sin 2\pi u_1 \sqrt{-2\ln u_2} \quad \text{and} \quad z_2 = \cos 2\pi u_1 \sqrt{-2\ln u_2} \tag{30.5}$$

are independent and Gaussian distributed with mean 0 and $\sigma = 1$.

There are many faster variants of this basic algorithm. For example, construct $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$, which are uniform on $(-1,1)$. Calculate $r^2 = v_1^2 + v_2^2$, and if $r^2 > 1$ start over. If $r^2 < 1$, it is uniform on (0,1). Then

$$z_1 = v_1 \sqrt{\frac{-2\ln r^2}{r^2}} \quad \text{and} \quad z_2 = v_2 \sqrt{\frac{-2\ln r^2}{r^2}} \tag{30.6}$$

are independent numbers chosen from a normal distribution with mean 0 and variance 1. $z_i' = \mu + \sigma z_i$ distributes with mean μ and variance σ^2.

For a multivariate Gaussian, see the algorithm in Ref. 10.

30.4.3. $\chi^2(n)$ distribution:

For n even, generate $n/2$ uniform numbers u_i; then

$$y = -2\ln\left(\prod_{i=1}^{n/2} u_i\right) \quad \text{is} \quad \chi^2(n)\ . \tag{30.7}$$

For n odd, generate $(n-1)/2$ uniform numbers u_i and one Gaussian z as in Sec. 30.4.2; then

$$y = -2\ln\left(\prod_{i=1}^{(n-1)/2} u_i\right) + z^2 \quad \text{is} \quad \chi^2(n)\ . \tag{30.8}$$

For $n \gtrsim 30$ the much faster Gaussian approximation for the χ^2 may be preferable: generate z as in Sec. 30.4.2 and use $y = \left[z + \sqrt{2n-1}\right]^2/2$; if $z < -\sqrt{2n-1}$ reject and start over.

30.4.4. *Gamma distribution*:

All of the following algorithms are given for $\lambda = 1$. For $\lambda \neq 1$, divide the resulting random number x by λ.

- If $k = 1$ (the *exponential* distribution), accept $x = -(\ln u)$.
- If $0 < k < 1$, initialize with $v_1 = (e + k)/e$ (with $e = 2.71828\ldots$ being the natural log base). Generate u_1, u_2. Define $v_2 = v_1 u_1$.

  Case 1: $v_2 \le 1$. Define $x = v_2^{1/k}$. If $u_2 \le e^{-x}$, accept x and stop, else restart by generating new u_1, u_2.
  Case 2: $v_2 > 1$. Define $x = -\ln([v_1 - v_2]/k)$. If $u_2 \le x^{k-1}$, accept x and stop, else restart by generating new u_1, u_2. Note that, for $k < 1$, the probability density has a pole at $x = 0$, so that return values of zero due to underflow must be accepted or otherwise dealt with.

- Otherwise, if $k > 1$, initialize with $c = 3k - 0.75$. Generate u_1 and compute $v_1 = u_1(1 - u_1)$ and $v_2 = (u_1 - 0.5)\sqrt{c/v_1}$. If $x = k + v_2 - 1 \le 0$, go back and generate new u_1; otherwise generate u_2 and compute $v_3 = 64 v_1^3 u_2^2$. If $v_3 \le 1 - 2v_2^2/x$ or if $\ln v_3 \le 2\{[k-1]\ln[x/(k-1)] - v_2\}$, accept x and stop; otherwise go back and generate new u_1.

30.4.5. *Binomial distribution*:

If $p \le 1/2$, iterate until a successful choice is made: begin with $k = 1$; compute $P_k = q^n$ [for $k \neq 1$ use $P_k \equiv f(r_k; n, p)$, and store P_k into B; generate u. If $u \le B$ accept $r_k = k - 1$ and stop; otherwise increment k by 1 and compute next P_k and add to B; generate a new u and repeat. If we arrive at $k = n + 1$, stop and accept $r_{n+1} = n$. If $p > 1/2$ it will be more efficient to generate r from $f(r; n, q)$, *i.e.*, with p and q interchanged, and then set $r_k = n - r$.

30.4.6. *Poisson distribution*:

Iterate until a successful choice is made: Begin with $k = 1$ and set $A = 1$ to start. Generate u. Replace A with uA; if now $A < \exp(-\mu)$, where μ is the Poisson parameter, accept $n_k = k - 1$ and stop. Otherwise increment k by 1, generate a new u and repeat, always starting with the value of A left from the previous try. For large $\mu(\gtrsim 10)$ it may be satisfactory (and much faster) to approximate the Poisson distribution by a Gaussian distribution (see our Probability chapter, Sec. 28.3.3) and generate z from $f(z;0,1)$; then accept $x = \max(0, [\mu + z\sqrt{\mu} + 0.5])$ where [ ] signifies the greatest integer $\le$ the expression.

30.4.7. *Student's t* distribution:

For $n > 0$ degrees of freedom (n not necessarily integer), generate x from a Gaussian with mean 0 and $\sigma^2 = 1$ according to the method of 30.4.2. Next generate y, an independent gamma random variate with $k = n/2$ degrees of freedom. Then $z = x\sqrt{2n}/\sqrt{y}$ is distributed as a t with n degrees of freedom.

For the special case $n = 1$, the Breit-Wigner distribution, generate u_1 and u_2; set $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$. If $v_1^2 + v_2^2 \le 1$ accept $z = v_1/v_2$ as a Breit-Wigner distribution with unit area, center at 0.0, and FWHM 2.0. Otherwise start over. For center M_0 and FWHM Γ, use $W = z\Gamma/2 + M_0$.

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31. MONTE CARLO PARTICLE NUMBERING SCHEME

Revised April 1998 by L. Garren (Fermilab), I.G. Knowles (Edinburgh U.), T. Sjöstrand (Lund U.), and T. Trippe (LBNL).

The PDG particle numbering scheme [1] is designed to facilitate interfacing between the event generator and analysis packages used in particle physics. It is used in several generators, *e.g.* HERWIG and PYTHIA/JETSET, and in the /HEPEVT/ [2] standard interface. After consultation [3], the scheme has been revised to better match the practice of program authors. The revised scheme includes numbering of states by orbital and radial quantum numbers to allow systematic inclusion of quark model states which are as yet undiscovered, and also includes numbering for hypothetical particles such as SUSY particles. The general form is a 7-digit number:

$$\pm n\, n_r\, n_L\, n_{q_1}\, n_{q_2}\, n_{q_3}\, n_J \; .$$

This encodes information about the particle's spin, flavor content, and internal quantum numbers. The details are as follows:

1. Particles are given positive numbers, antiparticles negative numbers. The PDG convention for mesons is used, so that K^+ and B^+ are particles.
2. Quarks and leptons are numbered consecutively starting from 1 and 11 respectively; to do this they are first ordered by family and within families by weak isospin.
3. In composite quark systems (diquarks, mesons, and baryons) $n_{q_{1-3}}$ are quark numbers used to specify the quark content, while the rightmost digit $n_J = 2J+1$ gives the system's spin (except for the K^0_S and K^0_L). The scheme does not cover particles of spin $J > 4$.
4. Diquarks have 4-digit numbers with $n_{q_1} \geq n_{q_2}$ and $n_{q_3} = 0$.
5. The numbering of mesons is guided by the nonrelativistic (L–S decoupled) quark model, as listed in Table 13.2. This leads to several differences with the earlier numbering [4] for excited mesons.
   a. The numbers specifying the meson's quark content conform to the convention $n_{q_1} = 0$ and $n_{q_2} \geq n_{q_3}$. The special case K^0_L is the sole exception to this rule.
   b. The quark numbers of flavorless, light (u, d, s) mesons are: 11 for the member of the isotriplet ($\pi^0, \rho^0, \ldots$), 22 for the lighter isosinglet ($\eta, \omega, \ldots$), and 33 for the heavier isosinglet ($\eta', \phi, \ldots$). Since isosinglet mesons are often large mixtures of $u\overline{u} + d\overline{d}$ and $s\overline{s}$ states, 22 and 33 are assigned by mass and do not necessarily specify the dominant quark composition.
   c. The special numbers 310 and 130 are given to the K^0_S and K^0_L respectively.
   d. The fifth digit n_L is reserved to distinguish mesons of the same total (J) but different spin (S) and orbital (L) angular momentum quantum numbers. For $J > 0$ the numbers are: $(L, S) = (J-1, 1)$ $n_L = 0$, $(J, 0)$ $n_L = 1$, $(J, 1)$ $n_L = 2$ and $(J+1, 1)$ $n_L = 3$. For the exceptional case $J = 0$ the numbers are $(0,0)$ $n_L = 0$ and $(1,1)$ $n_L = 1$ (*i.e.* $n_L = L$). See Table 31.1.

Table 31.1: Meson numbering logic. Here qq stands for $n_{q2}\, n_{q3}$.

	$L = J-1, S = 1$			$L = J, S = 0$			$L = J, S = 1$			$L = J+1, S = 1$		
J	code	J^{PC}	L	code	J^{PC}	L	code	J^{PC}	L	code	J^{PC}	L
0	—	—	—	00qq1	0^{-+}	0	—	—	—	10qq1	0^{++}	1
1	00qq3	1^{--}	0	10qq3	1^{+-}	1	20qq3	1^{++}	1	30qq3	1^{--}	2
2	00qq5	2^{++}	1	10qq5	2^{-+}	2	20qq5	2^{--}	2	30qq5	2^{++}	3
3	00qq7	3^{--}	2	10qq7	3^{+-}	3	20qq7	3^{++}	3	30qq7	3^{--}	4
4	00qq9	4^{++}	3	10qq9	4^{-+}	4	20qq9	4^{--}	4	30qq9	4^{++}	5

   e. If a set of physical mesons correspond to a (non-negligible) mixture of basis states, differing in their internal quantum numbers, then the lightest physical state gets the smallest basis state number. For example the $K_1(1270)$ is numbered 10313 (1^1P_1 K_{1B}) and the $K_1(1400)$ is numbered 20313 (1^3P_1 K_{1A}).
   f. The sixth digit n_r is used to label mesons radially excited above the ground state.
   g. Numbers have been assigned for complete $n_r = 0$ S- and P-wave multiplets, even where states remain to be identified.
   h. In some instances assignments within the $q\overline{q}$ meson model are only tentative; here best guess assignments are made.
   i. Many states appearing in the Meson Listings are not yet assigned within the $q\overline{q}$ model. Here $n_{q_{2-3}}$ and n_J are assigned according to the state's likely flavors and spin; all such unassigned light isoscalar states are given the flavor code 22. Within these groups $n_L = 0, 1, 2, \ldots$ is used to distinguish states of increasing mass. These states are flagged using $n = 9$. It is to be expected that these numbers will evolve as the nature of the states are elucidated.
6. The numbering of baryons is again guided by the nonrelativistic quark model, see Table 13.4.
   a. The numbers specifying a baryon's quark content are such that in general $n_{q_1} \geq n_{q_2} \geq n_{q_3}$.
   b. Two states exist for $J = 1/2$ baryons containing 3 different types of quarks. In the lighter baryon ($\Lambda, \Xi, \Omega, \ldots$) the light quarks are in an antisymmetric ($J = 0$) state while for the heavier baryon ($\Sigma^0, \Xi', \Omega', \ldots$) they are in a symmetric ($J = 1$) state. In this situation n_{q_2} and n_{q_3} are reversed for the lighter state, so that the smaller number corresponds to the lighter baryon.
   c. At present most Monte Carlos do not include excited baryons and no systematic scheme has been developed to denote them, though one is foreseen. In the meantime, use of the PDG 96 [4] numbers for excited baryons is recommended.
7. The gluon, when considered as a gauge boson, has official number 21. In codes for glueballs, however, 9 is used to allow a notation in close analogy with that of hadrons.
8. The pomeron and odderon trajectories and a generic reggeon trajectory of states in QCD are assigned codes 990, 9990, and 110 respectively, where the final 0 indicates the indeterminate nature of the spin, and the other digits reflect the expected "valence" flavor content. We do not attempt a complete classification of all reggeon trajectories, since there is currently no need to distinguish a specific such trajectory from its lowest-lying member.
9. Two-digit numbers in the range 21–30 are provided for the Standard Model gauge bosons and Higgs.
10. Codes 81–100 are reserved for generator-specific pseudoparticles and concepts.
11. The search for physics beyond the Standard Model is an active area, so these codes are also standardized as far as possible.
    a. A standard fourth generation of fermions is included by analogy with the first three.
    b. The graviton and the boson content of a two-Higgs-doublet scenario and of additional SU(2)×U(1) groups are found in the range 31–40.
    c. "One-of-a-kind" exotic particles are assigned numbers in the range 41–80.
    d. Fundamental supersymmetric particles are identified by adding a nonzero n to the particle number. The superpartner of a boson or a left-handed fermion has $n = 1$ while the superpartner of a right-handed fermion has $n = 2$. When mixing occurs, such as between the winos and charged Higgsinos to give charginos, or between left and right sfermions, the lighter physical state is given the smaller basis state number.
    e. Technicolor states have $n = 3$. In the absence of a unique theory we only number generic states whose digits reflect the techniquark content.
    f. Excited (composite) quarks and leptons are identified by setting $n = 4$.

12. Occasionally program authors add their own states. To avoid confusion, these should be flagged by setting $nn_r = 99$.
13. Concerning the non-99 numbers, it may be noted that only quarks, excited quarks, squarks, and diquarks have $n_{q_3} = 0$; only diquarks, baryons, and the odderon have $n_{q_1} \neq 0$; and only mesons, the reggeon, and the pomeron have $n_{q_1} = 0$ and $n_{q_2} \neq 0$. Concerning mesons (not antimesons), if n_{q_1} is odd then it labels a quark and an antiquark if even.

This text and lists of particle numbers can be found on the WWW [5]. The StdHep Monte Carlo standardization project [6] maintains the list of PDG particle numbers, as well as numbering schemes from most event generators and software to convert between the different schemes.

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QUARKS

d	1
u	2
s	3
c	4
b	5
t	6
b'	7
t'	8

LEPTONS

e^-	11
ν_e	12
μ^-	13
ν_μ	14
τ^-	15
ν_τ	16
τ'^-	17
$\nu_{\tau'}$	18

EXCITED PARTICLES

d^*	4000001
u^*	4000002
e^*	4000011
ν_e^*	4000012

GAUGE AND HIGGS BOSONS

g	(9) 21
γ	22
Z^0	23
W^+	24
h^0/H_1^0	25
Z'/Z_2^0	32
Z''/Z_3^0	33
W'/W_2^+	34
H^0/H_2^0	35
A^0/H_3^0	36
H^+	37

DIQUARKS

$(dd)_1$	1103
$(ud)_0$	2101
$(ud)_1$	2103
$(uu)_1$	2203
$(sd)_0$	3101
$(sd)_1$	3103
$(su)_0$	3201
$(su)_1$	3203
$(ss)_1$	3303
$(cd)_0$	4101
$(cd)_1$	4103
$(cu)_0$	4201
$(cu)_1$	4203
$(cs)_0$	4301
$(cs)_1$	4303
$(cc)_1$	4403
$(bd)_0$	5101
$(bd)_1$	5103
$(bu)_0$	5201
$(bu)_1$	5203
$(bs)_0$	5301
$(bs)_1$	5303
$(bc)_0$	5401
$(bc)_1$	5403
$(bb)_1$	5503

TECHNICOLOR PARTICLES

$\pi^0_{\rm tech}$	3000111
$\pi^+_{\rm tech}$	3000211
$\eta^0_{\rm tech}$	3000221
$\rho^0_{\rm tech}$	3000113
$\rho^+_{\rm tech}$	3000213
$\omega^0_{\rm tech}$	3000223

SUSY PARTICLES

$\tilde{d}_L$	1000001
$\tilde{u}_L$	1000002
$\tilde{s}_L$	1000003
$\tilde{c}_L$	1000004
$\tilde{b}_1$	1000005[a]
$\tilde{t}_1$	1000006[a]
$\tilde{e}_L^-$	1000011
$\tilde{\nu}_{eL}$	1000012
$\tilde{\mu}_L^-$	1000013
$\tilde{\nu}_{\mu L}$	1000014
$\tilde{\tau}_1^-$	1000015[a]
$\tilde{\nu}_{\tau L}$	1000016
$\tilde{d}_R$	2000001
$\tilde{u}_R$	2000002
$\tilde{s}_R$	2000003
$\tilde{c}_R$	2000004
$\tilde{b}_2$	2000005[a]
$\tilde{t}_2$	2000006[a]
$\tilde{e}_R^-$	2000011
$\tilde{\mu}_R^-$	2000013
$\tilde{\tau}_2^-$	2000015[a]
$\tilde{g}$	1000021
$\tilde{\chi}_1^0$	1000022[b]
$\tilde{\chi}_2^0$	1000023[b]
$\tilde{\chi}_1^+$	1000024[b]
$\tilde{\chi}_3^0$	1000025[b]
$\tilde{\chi}_4^0$	1000035[b]
$\tilde{\chi}_2^+$	1000037[b]
$\tilde{G}$	1000039

SPECIAL PARTICLES

G (graviton)	39
R^0	41
LQ^c	42
reggeon	110
pomeron	990
odderon	9990

for MC internal use 81–100

LIGHT $I = 1$ MESONS

π^0	111
π^+	211
$a_0(980)^0$	**9000111***
$a_0(980)^+$	**9000211***
$\pi(1300)^0$	**100111***
$\pi(1300)^+$	**100211***
$a_0(1450)^0$	**10111***
$a_0(1450)^+$	**10211***
$\pi(1800)^0$	200111
$\pi(1800)^+$	200211
$\rho(770)^0$	113
$\rho(770)^+$	213
$b_1(1235)^0$	10113
$b_1(1235)^+$	10213
$a_1(1260)^0$	20113
$a_1(1260)^+$	20213
$\hat{\rho}(1405)^0$	9000113
$\hat{\rho}(1405)^+$	9000213
$\rho(1450)^0$	**100113***
$\rho(1450)^+$	**100213***
$\rho(1700)^0$	30113
$\rho(1700)^+$	30213
$\rho(2150)^0$	9010113
$\rho(2150)^+$	9010213
$a_2(1320)^0$	115
$a_2(1320)^+$	215
$\pi_2(1670)^0$	10115
$\pi_2(1670)^+$	10215
$\pi_2(2100)^0$	9000115
$\pi_2(2100)^+$	9000215
$\rho_3(1690)^0$	117
$\rho_3(1690)^+$	217
$\rho_3(2250)^0$	9000117
$\rho_3(2250)^+$	9000217
$a_4(2040)^0$	119
$a_4(2040)^+$	219

LIGHT $I = 0$ MESONS

($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ Admixtures)

η	221
$\eta'(958)$	331
$f_0(400\text{–}1200)$	**9000221***
$f_0(980)$	**9010221***
$\eta(1295)$	**100221***
$f_0(1370)$	**10221***
$\eta(1440)$	**100331***
$f_0(1500)$	**9020221***
$f_J(1710)$	**9030221***
$\eta(1760)$	200221
$f_0(2020)$	9040221
$f_0(2060)$	9050221
$f_0(2200)$	**9060221***
$\eta(2225)$	**9070221***
$\omega(782)$	223
$\phi(1020)$	333
$h_1(1170)$	10223
$f_1(1285)$	20223
$h_1(1380)$	10333
$f_1(1420)$	**20333***
$\omega(1420)$	**100223***
$f_1(1510)$	**9000223***
$\omega(1600)$	**30223***
$\phi(1680)$	**100333***
$f_2(1270)$	225
$f_2(1430)$	9000225
$f_2'(1525)$	335
$f_2(1565)$	9010225
$f_2(1640)$	9020225
$\eta_2(1645)$	10225
$f_2(1810)$	100225
$\eta_2(1870)$	**10335***
$f_2(1950)$	**9030225***
$f_2(2010)$	**100335***
$f_2(2150)$	**9040225***
$f_2(2300)$	**9050225***
$f_2(2340)$	**9060225***
$\omega_3(1670)$	227
$\phi_3(1850)$	337
$f_4(2050)$	229
$f_J(2220)$	9000339
$f_4(2300)$	9000229

STRANGE MESONS	
K_L^0	130
K_S^0	310
K^0	311
K^+	321
$K_0^*(1430)^0$	10311
$K_0^*(1430)^+$	10321
$K(1460)^0$	100311
$K(1460)^+$	100321
$K(1830)^0$	200311
$K(1830)^+$	200321
$K_0^*(1950)^0$	9000311
$K_0^*(1950)^+$	9000321
$K^*(892)^0$	313
$K^*(892)^+$	323
$K_1(1270)^0$	10313
$K_1(1270)^+$	10323
$K_1(1400)^0$	20313
$K_1(1400)^+$	20323
$K^*(1410)^0$	**100313***
$K^*(1410)^+$	**100323***
$K_1(1650)^0$	9000313
$K_1(1650)^+$	9000323
$K^*(1680)^0$	**30313***
$K^*(1680)^+$	**30323***
$K_2^*(1430)^0$	315
$K_2^*(1430)^+$	325
$K_2(1580)^0$	9000315
$K_2(1580)^+$	9000325
$K_2(1770)^0$	10315
$K_2(1770)^+$	10325
$K_2(1820)^0$	20315
$K_2(1820)^+$	20325
$K_2^*(1980)^0$	100315
$K_2^*(1980)^+$	100325
$K_2(2250)^0$	9010315
$K_2(2250)^+$	9010325
$K_3^*(1780)^0$	317
$K_3^*(1780)^+$	327
$K_3(2320)^0$	9010317
$K_3(2320)^+$	9010327
$K_4^*(2045)^0$	319
$K_4^*(2045)^+$	329
$K_4(2500)^0$	9000319
$K_4(2500)^+$	9000329

CHARMED MESONS	
D^+	411
D^0	421
D_0^{*+}	10411
D_0^{*0}	10421
$D^*(2010)^+$	413
$D^*(2007)^0$	423
$D_1(2420)^+$	10413
$D_1(2420)^0$	10423
$D_1(H)^+$	20413
$D_1(H)^0$	20423
$D_2^*(2460)^+$	415
$D_2^*(2460)^0$	425
D_s^+	431
D_{s0}^{*+}	10431
D_s^{*+}	433
$D_{s1}(2536)^+$	10433
$D_{s1}(H)^+$	20433
D_{s2}^{*+}	435

BOTTOM MESONS	
B^0	511
B^+	521
B_0^{*0}	10511
B_0^{*+}	10521
B^{*0}	513
B^{*+}	523
$B_1(L)^0$	10513
$B_1(L)^+$	10523
$B_1(H)^0$	20513
$B_1(H)^+$	20523
B_2^{*0}	515
B_2^{*+}	525
B_s^0	531
B_{s0}^{*0}	10531
B_s^{*0}	533
$B_{s1}(L)^0$	10533
$B_{s1}(H)^0$	20533
B_{s2}^{*0}	535
B_c^+	541
B_{c0}^{*+}	10541
B_c^{*+}	543
$B_{c1}(L)^+$	10543
$B_{c1}(H)^+$	20543
B_{c2}^{*+}	545

$c\bar{c}$ MESONS	
$\eta_c(1S)$	441
$\chi_{c0}(1P)$	10441
$\eta_c(2S)$	100441
$J/\psi(1S)$	443
$h_c(1P)$	10443
$\chi_{c1}(1P)$	**20443***
$\psi(2S)$	**100443***
$\psi(3770)$	30443
$\psi(4040)$	**9000443***
$\psi(4160)$	**9010443***
$\psi(4415)$	**9020443***
$\chi_{c2}(1P)$	445

$b\bar{b}$ MESONS	
$\eta_b(1S)$	551
$\chi_{b0}(1P)$	**10551***
$\eta_b(2S)$	100551
$\chi_{b0}(2P)$	**110551***
$\eta_b(3S)$	200551
$\chi_{b0}(3P)$	210551
$\Upsilon(1S)$	553
$h_b(1P)$	10553
$\chi_{b1}(1P)$	**20553***
$\Upsilon_1(1D)$	30553
$\Upsilon(2S)$	**100553***
$h_b(2P)$	110553
$\chi_{b1}(2P)$	**120553***
$\Upsilon_1(2D)$	130553
$\Upsilon(3S)$	**200553***
$h_b(3P)$	210553
$\chi_{b1}(3P)$	220553
$\Upsilon(4S)$	**300553***
$\Upsilon(10860)$	**9000553***
$\Upsilon(11020)$	**9010553***
$\chi_{b2}(1P)$	555
$\eta_{b2}(1D)$	10555
$\Upsilon_2(1D)$	20555
$\chi_{b2}(2P)$	**100555***
$\eta_{b2}(2D)$	110555
$\Upsilon_2(2D)$	120555
$\chi_{b2}(3P)$	200555
$\Upsilon_3(1D)$	557
$\Upsilon_3(2D)$	100557

LIGHT BARYONS	
p	2212
n	2112
Δ^{++}	2224
Δ^+	2214
Δ^0	2114
Δ^-	1114

STRANGE BARYONS	
Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314
Ω^-	3334^d

CHARMED BARYONS	
Λ_c^+	4122
Σ_c^{++}	4222
Σ_c^+	4212
Σ_c^0	4112
Σ_c^{*++}	4224
Σ_c^{*+}	4214
Σ_c^{*0}	4114
Ξ_c^+	**4232***
Ξ_c^0	**4132***
$\Xi_c^{\prime +}$	4322
$\Xi_c^{\prime 0}$	4312
Ξ_c^{*+}	4324
Ξ_c^{*0}	4314
Ω_c^0	4332
Ω_c^{*0}	4334
Ξ_{cc}^+	4412
Ξ_{cc}^{++}	4422
Ξ_{cc}^{*+}	4414
Ξ_{cc}^{*++}	4424
Ω_{cc}^+	4432
Ω_{cc}^{*+}	4434
Ω_{ccc}^{++}	4444

BOTTOM BARYONS	
Λ_b^0	5122
Σ_b^-	5112
Σ_b^0	5212
Σ_b^+	5222
Σ_b^{*-}	5114
Σ_b^{*0}	5214
Σ_b^{*+}	5224
Ξ_b^-	5132
Ξ_b^0	5232
$\Xi_b^{\prime -}$	5312
$\Xi_b^{\prime 0}$	5322
Ξ_b^{*-}	5314
Ξ_b^{*0}	5324
Ω_b^-	5332
Ω_b^{*-}	5334
Ξ_{bc}^0	5142
Ξ_{bc}^+	5242
$\Xi_{bc}^{\prime 0}$	5412
$\Xi_{bc}^{\prime +}$	5422
Ξ_{bc}^{*0}	5414
Ξ_{bc}^{*+}	5424
Ω_{bc}^0	5342
$\Omega_{bc}^{\prime 0}$	5432
Ω_{bc}^{*0}	5434
Ω_{bcc}^+	5442
Ω_{bcc}^{*+}	5444
Ξ_{bb}^-	5512
Ξ_{bb}^0	5522
Ξ_{bb}^{*-}	5514
Ξ_{bb}^{*0}	5524
Ω_{bb}^-	5532
Ω_{bb}^{*-}	5534
Ω_{bbc}^0	5542
Ω_{bbc}^{*0}	5544
Ω_{bbb}^-	5554

Footnotes to the Tables:

*) Numbers which have changed since the 1996 *Review* [4] are in bold face.
Numbers which were not assigned in the 1996 *Review* [4] are in regular type.

a) Particulary in the third generation, the left and right sfermion states may mix, as shown. The lighter mixed state is given the smaller number.

b) The physical $\widetilde{\chi}$ states are admixtures of the pure $\widetilde{\gamma}$, $\widetilde{Z}^0$, $\widetilde{W}^+$, $\widetilde{H}_1^0$, $\widetilde{H}_2^0$, and $\widetilde{H}^+$ states.

c) In this draft we have only provided one generic leptoquark code. More general classifications according to spin, weak isospin and flavor content would lead to a host of states, that could be added as the need arises.

d) Σ^* and Ξ^* are alternate names for $\Sigma(1385)$ and $\Xi(1530)$.

32. CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND *d* FUNCTIONS

Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for $-8/15$ read $-\sqrt{8/15}$.

Notation:

		J	J	...
		M	M	...
m_1	m_2	Coefficients		
m_1	m_2			
⋮	⋮			

1/2×1/2

		1
		+1
+1/2	+1/2	1

		1	0
		0	0
+1/2	-1/2	1/2	1/2
-1/2	+1/2	1/2	-1/2

		1
		-1
-1/2	-1/2	1

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\Big(\frac{3}{2}\cos^2\theta - \frac{1}{2}\Big)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

2×1/2

		5/2
		+5/2
+2	1/2	1

		5/2	3/2
		3/2	+3/2
+2	-1/2	1/5	4/5
+1	+1/2	4/5	-1/5

		5/2	3/2
		+1/2	+1/2
+1	-1/2	2/5	3/5
0	+1/2	3/5	-2/5

		5/2	3/2
		-1/2	-1/2
0	-1/2	3/5	2/5
-1	+1/2	2/5	-3/5

		5/2	3/2
		-3/2	-3/2
-1	-1/2	4/5	1/5
-2	+1/2	1/5	-4/5

		5/2
		-5/2
-2	-1/2	1

1×1/2

		3/2
		+3/2
+1	+1/2	1

		3/2	1/2
		+1/2	+1/2
+1	-1/2	1/3	2/3
0	+1/2	2/3	-1/3

		3/2	1/2
		-1/2	-1/2
0	-1/2	2/3	1/3
-1	+1/2	1/3	-2/3

		3/2
		-3/2
-1	-1/2	1

3/2×1/2

		2
		+2
+3/2	+1/2	1

		2	1
		+1	+1
+3/2	-1/2	1/4	3/4
+1/2	+1/2	3/4	-1/4

		2	1
		0	0
+1/2	-1/2	1/2	1/2
-1/2	+1/2	1/2	-1/2

		2	1
		-1	-1
-1/2	-1/2	3/4	1/4
-3/2	+1/2	1/4	-3/4

		2
		-2
-3/2	-1/2	1

2×1

		3
		+3
+2	+1	1

		3	2
		+2	+2
+2	0	1/3	2/3
+1	+1	2/3	-1/3

		3	2	1
		+1	+1	+1
+2	-1	1/15	1/3	3/5
+1	0	8/15	1/6	-3/10
0	+1	6/15	-1/2	1/10

		3	2	1
		0	0	0
+1	-1	1/5	1/2	3/10
0	0	3/5	0	-2/5
-1	+1	1/5	-1/2	3/10

		3	2	1
		-1	-1	-1
0	-1	6/15	1/2	1/10
-1	0	8/15	-1/6	-3/10
-2	+1	1/15	-1/3	3/5

		3	2
		-2	-2
-1	-1	2/3	1/3
-2	0	1/3	-2/3

		3
		-3
-2	-1	1

3/2×1

		5/2
		+5/2
+3/2	+1	1

		5/2	3/2
		+3/2	+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	-2/5

		5/2	3/2	1/2
		+1/2	+1/2	+1/2
+3/2	-1	1/10	2/5	1/2
+1/2	0	3/5	1/15	-1/3
-1/2	+1	3/10	-8/15	1/6

		5/2	3/2	1/2
		-1/2	-1/2	-1/2
+1/2	-1	3/10	8/15	1/6
-1/2	0	3/5	-1/15	-1/3
-3/2	+1	1/10	-2/5	1/2

		5/2	3/2
		-3/2	-3/2
-1/2	-1	3/5	2/5
-3/2	0	2/5	-3/5

		5/2
		-5/2
-3/2	-1	1

1×1

		2
		+2
+1	+1	1

		2	1
		+1	+1
+1	0	1/2	1/2
0	+1	1/2	-1/2

		2	1	0
		0	0	0
+1	-1	1/6	1/2	1/3
0	0	2/3	0	-1/3
-1	+1	1/6	-1/2	1/3

		2	1
		-1	-1
0	-1	1/2	1/2
-1	0	1/2	-1/2

		2
		-2
-1	-1	1

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\,Y_\ell^m\, e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

3/2×3/2

		3
		+3
+3/2	+3/2	1

		3	2
		+2	+2
+3/2	+1/2	1/2	1/2
+1/2	+3/2	1/2	-1/2

		3	2	1
		+1	+1	+1
+3/2	-1/2	1/5	1/2	3/10
+1/2	+1/2	3/5	0	-2/5
-1/2	+3/2	1/5	-1/2	3/10

		3	2	1	0
		0	0	0	0
+3/2	-3/2	1/20	1/4	9/20	1/4
+1/2	-1/2	9/20	1/4	-1/20	-1/4
-1/2	+1/2	9/20	-1/4	-1/20	1/4
-3/2	+3/2	1/20	-1/4	9/20	-1/4

		3	2	1
		-1	-1	-1
+1/2	-3/2	1/5	1/2	3/10
-1/2	-1/2	3/5	0	-2/5
-3/2	+1/2	1/5	-1/2	3/10

		3	2
		-2	-2
-1/2	-3/2	1/2	1/2
-3/2	-1/2	1/2	-1/2

		3
		-3
-3/2	-3/2	1

$$d^1_{0,0} = \cos\theta \qquad d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^1_{1,1} = \frac{1+\cos\theta}{2}$$

$$d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

$$d^1_{1,-1} = \frac{1-\cos\theta}{2}$$

2×3/2

		7/2
		+7/2
+2	+3/2	1

		7/2	5/2
		+5/2	+5/2
+2	+1/2	3/7	4/7
+1	+3/2	4/7	-3/7

		7/2	5/2	3/2
		+3/2	+3/2	+3/2
+2	-1/2	1/7	16/35	2/5
+1	1/2	4/7	1/35	-2/5
0	3/2	2/7	-18/35	1/5

		7/2	5/2	3/2	1/2
		+1/2	+1/2	+1/2	+1/2
+2	-3/2	1/35	6/35	2/5	2/5
+1	-1/2	12/35	5/14	0	-3/10
0	1/2	18/35	-3/35	-1/5	1/5
-1	3/2	4/35	-27/70	2/5	-1/10

		7/2	5/2	3/2	1/2
		-1/2	-1/2	-1/2	-1/2
+1	-3/2	4/35	27/70	2/5	1/10
0	-1/2	18/35	3/35	-1/5	-1/5
-1	1/2	12/35	-5/14	0	3/10
-2	3/2	1/35	-6/35	2/5	-2/5

		7/2	5/2	3/2
		-3/2	-3/2	-3/2
0	-3/2	2/7	18/35	1/5
-1	-1/2	4/7	-1/35	-2/5
-2	1/2	1/7	-16/35	2/5

		7/2	5/2
		-5/2	-5/2
-1	-3/2	4/7	3/7
-2	-1/2	3/7	-4/7

		7/2
		-7/2
-2	-3/2	1

2×2

		4
		4
+2	+2	1

		4	3
		+3	+3
+2	+1	1/2	1/2
+1	+2	1/2	-1/2

		4	3	2
		+2	+2	+2
+2	0	3/14	1/2	2/7
+1	1	4/7	0	-3/7
0	2	3/14	-1/2	2/7

		4	3	2	1
		+1	+1	+1	+1
+2	-1	1/14	3/10	3/7	1/5
+1	0	3/7	1/5	-1/14	-3/10
0	1	3/7	-1/5	-1/14	3/10
-1	2	1/14	-3/10	3/7	-1/5

		4	3	2	1	0
		0	0	0	0	0
+2	-2	1/70	1/10	2/7	2/5	1/5
+1	-1	8/35	2/5	1/14	-1/10	-1/5
0	0	18/35	0	-2/7	0	1/5
-1	1	8/35	-2/5	1/14	1/10	-1/5
-2	2	1/70	-1/10	2/7	-2/5	1/5

		4	3	2	1
		-1	-1	-1	-1
+1	-2	1/14	3/10	3/7	1/5
0	-1	3/7	1/5	-1/14	-3/10
-1	0	3/7	-1/5	-1/14	3/10
-2	1	1/14	-3/10	3/7	-1/5

		4	3	2
		-2	-2	-2
0	-2	3/14	1/2	2/7
-1	-1	4/7	0	-3/7
-2	0	3/14	-1/2	2/7

		4	3
		-3	-3
-1	-2	1/2	1/2
-2	-1	1/2	-1/2

		4
		-4
-2	-2	1

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,1/2} = -\sqrt{3}\frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3,2}_{3/2,-1/2} = \sqrt{3}\frac{1-\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3,2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \Big(\frac{1+\cos\theta}{2}\Big)^2$$

$$d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta$$

$$d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta$$

$$d^2_{2,-2} = \Big(\frac{1-\cos\theta}{2}\Big)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1)$$

$$d^2_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta$$

$$d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1) \qquad d^2_{0,0} = \Big(\frac{3}{2}\cos^2\theta - \frac{1}{2}\Big)$$

Figure 32.1: The sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The coefficients here have been calculated using computer programs written independently by Cohen and at LBNL.

33. SU(3) ISOSCALAR FACTORS AND REPRESENTATION MATRICES

Written by R.L. Kelly (LBNL).

The most commonly used SU(3) isoscalar factors, corresponding to the singlet, octet, and decuplet content of $8 \otimes 8$ and $10 \otimes 8$, are shown at the right. The notation uses particle names to identify the coefficients, so that the pattern of relative couplings may be seen at a glance. We illustrate the use of the coefficients below. See J.J de Swart, Rev. Mod. Phys. **35**, 916 (1963) for detailed explanations and phase conventions.

A $\sqrt{\ }$ is to be understood over every integer in the matrices; the exponent $1/2$ on each matrix is a reminder of this. For example, the $\Xi \to \Omega K$ element of the $10 \to 10 \otimes 8$ matrix is $-\sqrt{6}/\sqrt{24} = -1/2$.

Intramultiplet relative decay strengths may be read directly from the matrices. For example, in decuplet → octet + octet decays, the ratio of $\Omega^* \to \Xi\overline{K}$ and $\Delta \to N\pi$ partial widths is, from the $10 \to 8 \times 8$ matrix,

$$\frac{\Gamma(\Omega^* \to \Xi\overline{K})}{\Gamma(\Delta \to N\pi)} = \frac{12}{6} \times \text{(phase space factors)} . \qquad (33.1)$$

Including isospin Clebsch-Gordan coefficients, we obtain, *e.g.*,

$$\frac{\Gamma(\Omega^{*-} \to \Xi^0 K^-)}{\Gamma(\Delta^+ \to p\pi^0)} = \frac{1/2}{2/3} \times \frac{12}{6} \times p.s.f. = \frac{3}{2} \times p.s.f. \qquad (33.2)$$

Partial widths for $8 \to 8 \otimes 8$ involve a linear superposition of 8_1 (symmetric) and 8_2 (antisymmetric) couplings. For example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim \left(-\sqrt{\frac{9}{20}}\, g_1 + \sqrt{\frac{3}{12}}\, g_2\right)^2 . \qquad (33.3)$$

The relations between g_1 and g_2 (with de Swart's normalization) and the standard D and F couplings that appear in the interaction Lagrangian,

$$\mathscr{L} = -\sqrt{2}\, D\, Tr\,(\{\overline{B}, B\}M) + \sqrt{2}\, F\, Tr\,([\overline{B}, B]\, M) \ , \qquad (33.4)$$

where $[\overline{B}, B] \equiv \overline{B}B - B\overline{B}$ and $\{\overline{B}, B\} \equiv \overline{B}B + B\overline{B}$, are

$$D = \frac{\sqrt{30}}{40}\, g_1 \ , \qquad F = \frac{\sqrt{6}}{24}\, g_2 \ . \qquad (33.5)$$

Thus, for example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim (F - D)^2 \sim (1 - 2\alpha)^2 \ , \qquad (33.6)$$

where $\alpha \equiv F/(D + F)$. (This definition of α is de Swart's. The alternative $D/(D + F)$, due to Gell-Mann, is also used.)

The generators of SU(3) transformations, λ_a $(a = 1, 8)$, are 3×3 matrices that obey the following commutation and anticommutation relationships:

$$[\lambda_a,\ \lambda_b] \equiv \lambda_a\lambda_b - \lambda_b\lambda_a = 2if_{abc}\lambda_c \qquad (33.7)$$

$$\{\lambda_a,\ \lambda_b\} \equiv \lambda_a\lambda_b + \lambda_b\lambda_a = \frac{4}{3}\delta_{ab}I + 2d_{abc}\lambda_c \ , \qquad (33.8)$$

where I is the 3×3 identity matrix, and δ_{ab} is the Kronecker delta symbol. The f_{abc} are odd under the permutation of any pair of indices, while the d_{abc} are even. The nonzero values are

$1 \to 8 \otimes 8$

$$(\Lambda) \ \to (N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K) \qquad = \frac{1}{\sqrt{8}}\,(2\ \ 3\ \ -1\ \ -2)^{1/2}$$

$8_1 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi\ \ N\eta\ \ \Sigma K\ \ \Lambda K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{20}} \begin{pmatrix} 9 & -1 & -9 & -1 & \\ -6 & 0 & 4 & 4 & -6 \\ 2 & -12 & -4 & -2 & \\ 9 & -1 & -9 & -1 & \end{pmatrix}^{1/2}$$

$8_2 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi\ \ N\eta\ \ \Sigma K\ \ \Lambda K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} 3 & 3 & 3 & -3 & \\ 2 & 8 & 0 & 0 & -2 \\ 6 & 0 & 0 & 6 & \\ 3 & 3 & 3 & -3 & \end{pmatrix}^{1/2}$$

$10 \to 8 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} N\pi\ \ \Sigma K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \\ \Xi\overline{K} \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} & & -6 & 6 & \\ -2 & 2 & -3 & 3 & 2 \\ 3 & -3 & 3 & 3 & \\ & & 12 & & \end{pmatrix}^{1/2}$$

$8 \to 10 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} \Delta\pi\ \ \Sigma K \\ \Delta\overline{K}\ \ \Sigma\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\pi\ \ \Xi K \\ \Sigma\overline{K}\ \ \Xi\pi\ \ \Xi\eta\ \ \Omega K \end{pmatrix} = \frac{1}{\sqrt{15}} \begin{pmatrix} & -12 & 3 & \\ 8 & -2 & -3 & 2 \\ & -9 & 6 & \\ 3 & -3 & -3 & 6 \end{pmatrix}^{1/2}$$

$10 \to 10 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} \Delta\pi\ \ \Delta\eta\ \ \Sigma K \\ \Delta\overline{K}\ \ \Sigma\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Xi\pi\ \ \Xi\eta\ \ \Omega K \\ \Xi\overline{K}\ \ \Omega\eta \end{pmatrix} = \frac{1}{\sqrt{24}} \begin{pmatrix} & 15 & 3 & -6 \\ 8 & 8 & 0 & -8 \\ 12 & 3 & -3 & -6 \\ & 12 & -12 & \end{pmatrix}^{1/2}$$

abc	f_{abc}	abc	d_{abc}	abc	d_{abc}
123	1	118	$1/\sqrt{3}$	355	$1/2$
147	$1/2$	146	$1/2$	366	$-1/2$
156	$-1/2$	157	$1/2$	377	$-1/2$
246	$1/2$	228	$1/\sqrt{3}$	448	$-1/(2\sqrt{3})$
257	$1/2$	247	$-1/2$	558	$-1/(2\sqrt{3})$
345	$1/2$	256	$1/2$	668	$-1/(2\sqrt{3})$
367	$-1/2$	338	$1/\sqrt{3}$	778	$-1/(2\sqrt{3})$
458	$\sqrt{3}/2$	344	$1/2$	888	$-1/\sqrt{3}$
678	$\sqrt{3}/2$				

The λ_a's are

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \ \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \ \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \ \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \ \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \ \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Equation (33.7) defines the Lie algebra of SU(3). A general d-dimensional representation is given by a set of $d \times d$ matrices satisfying Eq. (33.7) with the f_{abc} given above. Equation (33.8) is specific to the defining 3-dimensional representation.

34. SU(n) MULTIPLETS AND YOUNG DIAGRAMS

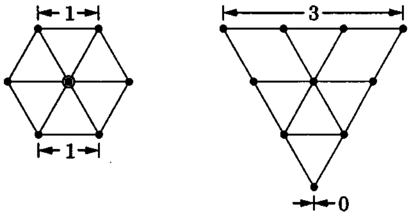
Written by C.G. Wohl (LBNL).

This note tells (1) how SU(n) particle multiplets are identified or labeled, (2) how to find the number of particles in a multiplet from its label, (3) how to draw the Young diagram for a multiplet, and (4) how to use Young diagrams to determine the overall multiplet structure of a composite system, such as a 3-quark or a meson-baryon system.

In much of the literature, the word "representation" is used where we use "multiplet," and "tableau" is used where we use "diagram."

34.1. Multiplet labels

An SU(n) multiplet is uniquely identified by a string of $(n-1)$ nonnegative integers: $(\alpha, \beta, \gamma, \ldots)$. Any such set of integers specifies a multiplet. For an SU(2) multiplet such as an isospin multiplet, the single integer α is the number of ***steps*** from one end of the multiplet to the other (*i.e.*, it is one fewer than the number of particles in the multiplet). In SU(3), the two integers α and β are the numbers of steps across the top and bottom levels of the multiplet diagram. Thus the labels for the SU(3) octet and decuplet



are (1,1) and (3,0). For larger n, the interpretation of the integers in terms of the geometry of the multiplets, which exist in an $(n-1)$-dimensional space, is not so readily apparent.

The label for the SU(n) singlet is $(0, 0, \ldots, 0)$. In a flavor SU(n), the n quarks together form a $(1, 0, \ldots, 0)$ multiplet, and the n antiquarks belong to a $(0, \ldots, 0, 1)$ multiplet. These two multiplets are ***conjugate*** to one another, which means their labels are related by $(\alpha, \beta, \ldots) \leftrightarrow (\ldots, \beta, \alpha)$.

34.2. Number of particles

The number of particles in a multiplet, $N = N(\alpha, \beta, \ldots)$, is given as follows (note the pattern of the equations).

In SU(2), $N = N(\alpha)$ is

$$N = \frac{(\alpha+1)}{1} . \tag{34.1}$$

In SU(3), $N = N(\alpha, \beta)$ is

$$N = \frac{(\alpha+1)}{1} \cdot \frac{(\beta+1)}{1} \cdot \frac{(\alpha+\beta+2)}{2} . \tag{34.2}$$

In SU(4), $N = N(\alpha, \beta, \gamma)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} . \tag{34.3}$$

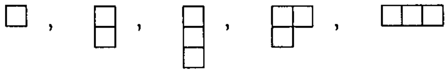
Note that in Eq. (34.3) there is no factor with $(\alpha + \gamma + 2)$: only a ***consecutive*** sequence of the label integers appears in any factor. One more example should make the pattern clear for any SU(n). In SU(5), $N = N(\alpha, \beta, \gamma, \delta)$ is

$$\begin{aligned} N = {} & \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\delta{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \\ & \times \frac{(\gamma{+}\delta{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \cdot \frac{(\beta{+}\gamma{+}\delta{+}3)}{3} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}\delta{+}4)}{4} \end{aligned} \tag{34.4}$$

From the symmetry of these equations, it is clear that multiplets that are conjugate to one another have the same number of particles, but so can other multiplets. For example, the SU(4) multiplets (3,0,0) and (1,1,0) each have 20 particles. Try the equations and see.

34.3. Young diagrams

A Young diagram consists of an array of boxes (or some other symbol) arranged in one or more ***left-justified*** rows, with each row being ***at least as long*** as the row beneath. The correspondence between a diagram and a multiplet label is: The top row juts out α boxes to the right past the end of the second row, the second row juts out β boxes to the right past the end of the third row, *etc.* A diagram in SU(n) has at most n rows. There can be any number of "completed" columns of n boxes buttressing the left of a diagram; these don't affect the label. Thus in SU(3) the diagrams

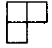


represent the multiplets (1,0), (0,1), (0,0), (1,1), and (3,0). In any SU(n), the quark multiplet is represented by a single box, the antiquark multiplet by a column of $(n-1)$ boxes, and a singlet by a completed column of n boxes.

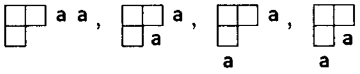
34.4. Coupling multiplets together

The following recipe tells how to find the multiplets that occur in coupling two multiplets together. To couple together more than two multiplets, first couple two, then couple a third with each of the multiplets obtained from the first two, *etc.*

First a definition: A sequence of the letters $a, b, c, \ldots$ is ***admissible*** if at any point in the sequence at least as many a's have occurred as b's, at least as many b's have occurred as c's, *etc.* Thus *abcd* and *aabcb* are admissible sequences and *abb* and *acb* are not. Now the recipe:

(a) Draw the Young diagrams for the two multiplets, but in one of the diagrams replace the boxes in the first row with a's, the boxes in the second row with b's, *etc.* Thus, to couple two SU(3) octets (such as the π-meson octet and the baryon octet), we start with  and $\begin{smallmatrix} a & a \\ b & \end{smallmatrix}$. The ***unlettered*** diagram forms the ***upper left-hand corner*** of all the enlarged diagrams constructed below.

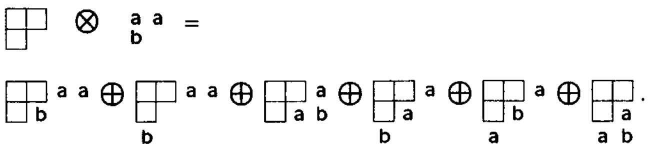
(b) Add the a's from the lettered diagram to the right-hand ends of the rows of the unlettered diagram to form all possible legitimate Young diagrams that have no more than one a per column. In general, there will be several distinct diagrams, and all the a's appear in each diagram. At this stage, for the coupling of the two SU(3) octets, we have:



(c) Use the b's to further enlarge the diagrams already obtained, subject to the same rules. Then throw away any diagram in which the full sequence of letters formed by reading ***right to left*** in the first row, then the second row, *etc.*, is not admissible.

(d) Proceed as in (c) with the c's (if any), *etc.*

The final result of the coupling of the two SU(3) octets is:



Here only the diagrams with admissible sequences of a's and b's and with fewer than four rows (since $n = 3$) have been kept. In terms of multiplet labels, the above may be written

$$(1,1) \otimes (1,1) = (2,2) \oplus (3,0) \oplus (0,3) \oplus (1,1) \oplus (1,1) \oplus (0,0) .$$

In terms of numbers of particles, it may be written

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} .$$

The product of the numbers on the left here is equal to the sum on the right, a useful check. (See also Sec. 13 on the Quark Model.)

35. KINEMATICS

Revised May 1996 by J.D. Jackson (LBNL).

Throughout this section units are used in which $\hbar = c = 1$. The following conversions are useful: $\hbar c = 197.3$ MeV fm, $(\hbar c)^2 = 0.3894$ (GeV)^2 mb.

35.1. Lorentz transformations

The energy E and 3-momentum $\boldsymbol{p}$ of a particle of mass m form a 4-vector $p = (E, \boldsymbol{p})$ whose square $p^2 \equiv E^2 - |\boldsymbol{p}|^2 = m^2$. The velocity of the particle is $\boldsymbol{\beta} = \boldsymbol{p}/E$. The energy and momentum $(E^*, \boldsymbol{p}^*)$ viewed from a frame moving with velocity $\boldsymbol{\beta}_f$ are given by

$$\begin{pmatrix} E^* \\ p^*_{\parallel} \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\parallel} \end{pmatrix} , \quad p^*_T = p_T , \tag{35.1}$$

where $\gamma_f = (1 - \beta_f^2)^{-1/2}$ and p_T $(p_{\parallel})$ are the components of $\boldsymbol{p}$ perpendicular (parallel) to $\boldsymbol{\beta}_f$. Other 4-vectors, such as the space-time coordinates of events, of course transform in the same way. The scalar product of two 4-momenta $p_1 \cdot p_2 = E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2$ is invariant (frame independent).

35.2. Center-of-mass energy and momentum

In the collision of two particles of masses m_1 and m_2 the total center-of-mass energy can be expressed in the Lorentz-invariant form

$$\begin{aligned} E_{\rm cm} &= \left[(E_1 + E_2)^2 - (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2\right]^{1/2} , \\ &= \left[m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta)\right]^{1/2} , \end{aligned} \tag{35.2}$$

where θ is the angle between the particles. In the frame where one particle (of mass m_2) is at rest (lab frame),

$$E_{\rm cm} = (m_1^2 + m_2^2 + 2E_{1\,\rm lab}\, m_2)^{1/2} . \tag{35.3}$$

The velocity of the center-of-mass in the lab frame is

$$\boldsymbol{\beta}_{\rm cm} = \boldsymbol{p}_{\rm lab}/(E_{1\,\rm lab} + m_2) , \tag{35.4}$$

where $\boldsymbol{p}_{\rm lab} \equiv \boldsymbol{p}_{1\,\rm lab}$ and

$$\gamma_{\rm cm} = (E_{1\,\rm lab} + m_2)/E_{\rm cm} . \tag{35.5}$$

The c.m. momenta of particles 1 and 2 are of magnitude

$$p_{\rm cm} = p_{\rm lab}\frac{m_2}{E_{\rm cm}} . \tag{35.6}$$

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

$$E_{\rm cm}\, dE_{\rm cm} = m_2\, dE_{1\,\rm lab} = m_2\, \beta_{1\,\rm lab}\, dp_{\rm lab} . \tag{35.7}$$

35.3. Lorentz-invariant amplitudes

The matrix elements for a scattering or decay process are written in terms of an invariant amplitude $-i\mathcal{M}$. As an example, the S-matrix for $2 \to 2$ scattering is related to $\mathcal{M}$ by

$$\begin{aligned} \langle p_1' p_2' \,|S|\, p_1 p_2\rangle &= I - i(2\pi)^4\, \delta^4(p_1 + p_2 - p_1' - p_2') \\ &\times \frac{\mathcal{M}(p_1, p_2; p_1', p_2')}{(2E_1)^{1/2}\,(2E_2)^{1/2}\,(2E_1')^{1/2}\,(2E_2')^{1/2}} . \end{aligned} \tag{35.8}$$

The state normalization is such that

$$\langle p'|p\rangle = (2\pi)^3 \delta^3(\boldsymbol{p} - \boldsymbol{p}') . \tag{35.9}$$

35.4. Particle decays

The partial decay rate of a particle of mass M into n bodies in its rest frame is given in terms of the Lorentz-invariant matrix element $\mathcal{M}$ by

$$d\Gamma = \frac{(2\pi)^4}{2M}\, |\mathcal{M}|^2\, d\Phi_n\,(P;\, p_1, \ldots, p_n), \tag{35.10}$$

where $d\Phi_n$ is an element of n-body phase space given by

$$d\Phi_n(P;\, p_1, \ldots, p_n) = \delta^4\,(P - \sum_{i=1}^{n} p_i)\, \prod_{i=1}^{n} \frac{d^3\boldsymbol{p}_i}{(2\pi)^3 2E_i} . \tag{35.11}$$

This phase space can be generated recursively, viz.

$$\begin{aligned} d\Phi_n(P;\, p_1, \ldots, p_n) &= d\Phi_j(q;\, p_1, \ldots, p_j) \\ &\times\; d\Phi_{n-j+1}\,(P;\, q, p_{i+1}, \ldots, p_n)(2\pi)^3 dq^2 , \end{aligned} \tag{35.12}$$

where $q^2 = (\sum_{i=1}^{j} E_i)^2 - \left|\sum_{i=1}^{j} \boldsymbol{p}_i\right|^2$. This form is particularly useful in the case where a particle decays into another particle that subsequently decays.

35.4.1. *Survival probability*:

If a particle of mass M has mean proper lifetime τ $(= 1/\Gamma)$ and has momentum $(E, \boldsymbol{p})$, then the probability that it lives for a time t_0 or greater before decaying is given by

$$P(t_0) = e^{-t_0\,\Gamma/\gamma} = e^{-Mt_0\,\Gamma/E} , \tag{35.13}$$

and the probability that it travels a distance x_0 or greater is

$$P(x_0) = e^{-Mx_0\,\Gamma/|\boldsymbol{p}|} . \tag{35.14}$$

35.4.2. *Two-body decays*:

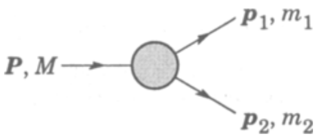


Figure 35.1: Definitions of variables for two-body decays.

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} , \tag{35.15}$$

$$\begin{aligned} |\boldsymbol{p}_1| &= |\boldsymbol{p}_2| \\ &= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M} , \end{aligned} \tag{35.16}$$

and

$$d\Gamma = \frac{1}{32\pi^2}\, |\mathcal{M}|^2\, \frac{|\boldsymbol{p}_1|}{M^2}\, d\Omega , \tag{35.17}$$

where $d\Omega = d\phi_1 d(\cos\theta_1)$ is the solid angle of particle 1.

35.4.3. *Three-body decays*:

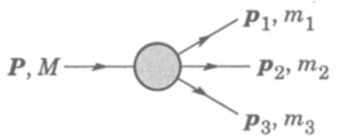


Figure 35.2: Definitions of variables for three-body decays.

Defining $p_{ij} = p_i + p_j$ and $m_{ij}^2 = p_{ij}^2$, then $m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$ and $m_{12}^2 = (P - p_3)^2 = M^2 + m_3^2 - 2ME_3$, where E_3 is the energy of particle 3 in the rest frame of M. In that frame, the momenta of the three decay particles lie in a plane. The relative orientation of these three momenta is fixed if their energies are known. The momenta can therefore be specified in space by giving three Euler angles (α, β, γ) that specify the orientation of the final system relative to the initial particle. Then

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} |\mathscr{M}|^2 \, dE_1 \, dE_2 \, d\alpha \, d(\cos\beta) \, d\gamma \, . \tag{35.18}$$

Alternatively

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M^2} |\mathscr{M}|^2 \, |\boldsymbol{p}_1^*| \, |\boldsymbol{p}_3| \, dm_{12} \, d\Omega_1^* \, d\Omega_3 \, , \tag{35.19}$$

where $(|\boldsymbol{p}_1^*|, \Omega_1^*)$ is the momentum of particle 1 in the rest frame of 1 and 2, and Ω_3 is the angle of particle 3 in the rest frame of the decaying particle. $|\boldsymbol{p}_1^*|$ and $|\boldsymbol{p}_3|$ are given by

$$|\boldsymbol{p}_1^*| = \frac{\left[\left(m_{12}^2 - (m_1 + m_2)^2\right)\left(m_{12}^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2m_{12}} \, , \tag{35.20a}$$

and

$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M} \, . \tag{35.20b}$$

[Compare with Eq. (35.16).]

If the decaying particle is a scalar or we average over its spin states, then integration over the angles in Eq. (35.18) gives

$$\begin{aligned} d\Gamma &= \frac{1}{(2\pi)^3} \frac{1}{8M} \overline{|\mathscr{M}|^2} \, dE_1 \, dE_2 \\ &= \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathscr{M}|^2} \, dm_{12}^2 \, dm_{23}^2 \, . \end{aligned} \tag{35.21}$$

This is the standard form for the Dalitz plot.

35.4.3.1. ***Dalitz plot:*** For a given value of m_{12}^2, the range of m_{23}^2 is determined by its values when $\boldsymbol{p}_2$ is parallel or antiparallel to $\boldsymbol{p}_3$:

$$\begin{aligned} &(m_{23}^2)_{\max} = \\ &(E_2^* + E_3^*)^2 - \left(\sqrt{E_2^{*2} - m_2^2} - \sqrt{E_3^{*2} - m_3^2}\right)^2 \, , \end{aligned} \tag{35.22a}$$

$$\begin{aligned} &(m_{23}^2)_{\min} = \\ &(E_2^* + E_3^*)^2 - \left(\sqrt{E_2^{*2} - m_2^2} + \sqrt{E_3^{*2} - m_3^2}\right)^2 \, . \end{aligned} \tag{35.22b}$$

Here $E_2^* = (m_{12}^2 - m_1^2 + m_2^2)/2m_{12}$ and $E_3^* = (M^2 - m_{12}^2 - m_3^2)/2m_{12}$ are the energies of particles 2 and 3 in the m_{12} rest frame. The scatter plot in m_{12}^2 and m_{23}^2 is called a Dalitz plot. If $\overline{|\mathscr{M}|^2}$ is constant, the allowed region of the plot will be uniformly populated with events [see Eq. (35.21)]. A nonuniformity in the plot gives immediate information on $|\mathscr{M}|^2$. For example, in the case of $D \to K\pi\pi$, bands appear when $m_{(K\pi)} = m_{K^*(892)}$, reflecting the appearance of the decay chain $D \to K^*(892)\pi \to K\pi\pi$.

35.4.4. ***Kinematic limits***: In a three-body decay the maximum of $|\boldsymbol{p}_3|$, [given by Eq. (35.20)], is achieved when $m_{12} = m_1 + m_2$, *i.e.*, particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition, $m_3 > m_1, m_2$, then $|\boldsymbol{p}_3|_{\max} > |\boldsymbol{p}_1|_{\max}, |\boldsymbol{p}_2|_{\max}$.

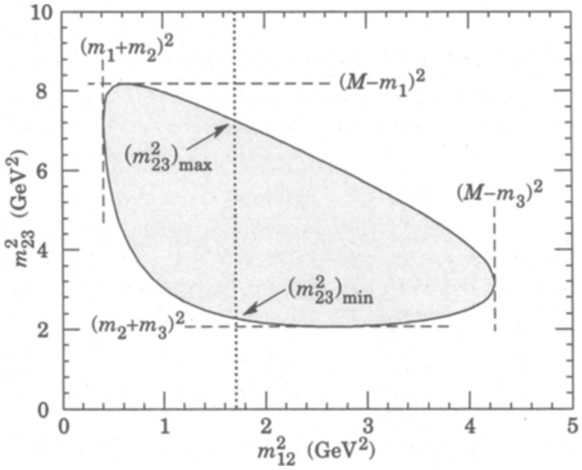


Figure 35.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

35.4.5. ***Multibody decays***: The above results may be generalized to final states containing any number of particles by combining some of the particles into "effective particles" and treating the final states as 2 or 3 "effective particle" states. Thus, if $p_{ijk\ldots} = p_i + p_j + p_k + \ldots$, then

$$m_{ijk\ldots} = \sqrt{p^2{}_{ijk\ldots}} \, , \tag{35.23}$$

and $m_{ijk\ldots}$ may be used in place of *e.g.*, m_{12} in the relations in Sec. 35.4.3 or 35.4.3.1 above.

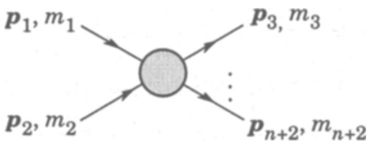


Figure 35.4: Definitions of variables for production of an n-body final state.

35.5. Cross sections

The differential cross section is given by

$$d\sigma = \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; \, p_3, \ldots, p_{n+2}) \, . \tag{35.24}$$

[See Eq. (35.11).] In the rest frame of m_2(lab),

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = m_2 p_{1\,\mathrm{lab}} \, ; \tag{35.25a}$$

while in the center-of-mass frame

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1\mathrm{cm}} \sqrt{s} \, . \tag{35.25b}$$

35.5.1. ***Two-body reactions:***

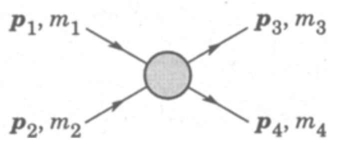


Figure 35.5: Definitions of variables for a two-body final state.

Two particles of momenta p_1 and p_2 and masses m_1 and m_2 scatter to particles of momenta p_3 and p_4 and masses m_3 and m_4; the Lorentz-invariant Mandelstam variables are defined by

$$\begin{aligned} s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\ &= m_1^2 + 2E_1E_2 - 2\mathbf{p}_1 \cdot \mathbf{p}_2 + m_2^2 \ , \qquad (35.26) \\ t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\ &= m_1^2 - 2E_1E_3 + 2\mathbf{p}_1 \cdot \mathbf{p}_3 + m_3^2 \ , \qquad (35.27) \\ u &= (p_1 - p_4)^2 = (p_2 - p_3)^2 \\ &= m_1^2 - 2E_1E_4 + 2\mathbf{p}_1 \cdot \mathbf{p}_4 + m_4^2 \ , \qquad (35.28) \end{aligned}$$

and they satisfy

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2 \ . \qquad (35.29)$$

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s}\frac{1}{|\mathbf{p}_{1\mathrm{cm}}|^2}|\mathscr{M}|^2 \ . \qquad (35.30)$$

In the center-of-mass frame

$$\begin{aligned} t &= (E_{1\mathrm{cm}} - E_{3\mathrm{cm}})^2 - (p_{1\mathrm{cm}} - p_{3\mathrm{cm}})^2 \qquad - 4p_{1\mathrm{cm}}\, p_{3\mathrm{cm}} \sin^2(\theta_{\mathrm{cm}}/2) \\ &= t_0 - 4p_{1\mathrm{cm}}\, p_{3\mathrm{cm}} \sin^2(\theta_{\mathrm{cm}}/2) \ , \qquad (35.31) \end{aligned}$$

where θ_{cm} is the angle between particle 1 and 3. The limiting values t_0 ($\theta_{\mathrm{cm}} = 0$) and t_1 ($\theta_{\mathrm{cm}} = \pi$) for 2 → 2 scattering are

$$t_0(t_1) = \left[\frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}}\right]^2 - (p_{1\,\mathrm{cm}} \mp p_{3\,\mathrm{cm}})^2 \ . \qquad (35.32)$$

In the literature the notation t_{min} (t_{max}) for t_0 (t_1) is sometimes used, which should be discouraged since $t_0 > t_1$. The center-of-mass energies and momenta of the incoming particles are

$$E_{1\mathrm{cm}} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}} \ , \qquad E_{2\mathrm{cm}} = \frac{s + m_2^2 - m_1^2}{2\sqrt{s}} \ , \qquad (35.33)$$

For $E_{3\mathrm{cm}}$ and $E_{4\mathrm{cm}}$, change m_1 to m_3 and m_2 to m_4. Then

$$p_{i\,\mathrm{cm}} = \sqrt{E_{i\,\mathrm{cm}}^2 - m_i^2} \text{ and } p_{1\mathrm{cm}} = \frac{p_{1\,\mathrm{lab}}\, m_2}{\sqrt{s}} \ . \qquad (35.34)$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (35.2)–(35.4).]

35.5.2. ***Inclusive reactions***: Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y \ , \qquad (35.35)$$

where m_T is the transverse mass

$$m_T^2 = m^2 + p_x^2 + p_y^2 \ , \qquad (35.36)$$

and the rapidity y is defined by

$$\begin{aligned} y &= \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) \\ &= \ln\left(\frac{E + p_z}{m_T}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) \ . \qquad (35.37) \end{aligned}$$

Under a boost in the z-direction to a frame with velocity β, $y \to y - \tanh^{-1}\beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E\frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi\, dy\, p_T dp_T} \Longrightarrow \frac{d^2\sigma}{\pi\, dy\, d(p_T^2)} \ . \qquad (35.38)$$

The second form is obtained using the identity $dy/dp_z = 1/E$, and the third form represents the average over ϕ.

Feynman's x variable is given by

$$x = \frac{p_z}{p_{z\,\mathrm{max}}} \approx \frac{E + p_z}{(E + p_z)_{\mathrm{max}}} \quad (p_T \ll |p_z|) \ . \qquad (35.39)$$

In the c.m. frame,

$$x \approx \frac{2p_{z\,\mathrm{cm}}}{\sqrt{s}} = \frac{2m_T \sinh y_{\mathrm{cm}}}{\sqrt{s}} \qquad (35.40)$$

and

$$= (y_{\mathrm{cm}})_{\mathrm{max}} = \ln(\sqrt{s}/m) \ . \qquad (35.41)$$

For $p \gg m$, the rapidity [Eq. (35.37)] may be expanded to obtain

$$\begin{aligned} y &= \frac{1}{2}\ln\frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots} \\ &\approx -\ln\tan(\theta/2) \equiv \eta \qquad (35.42) \end{aligned}$$

where $\cos\theta = p_z/p$. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $p \gg m$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\sinh\eta = \cot\theta \ , \quad \cosh\eta = 1/\sin\theta \ , \quad \tanh\eta = \cos\theta \ . \qquad (35.43)$$

35.5.3. ***Partial waves***: The amplitude in the center of mass for elastic scattering of spinless particles may be expanded in Legendre polynomials

$$f(k,\theta) = \frac{1}{k}\sum_\ell (2\ell + 1)a_\ell P_\ell(\cos\theta) \ , \qquad (35.44)$$

where k is the c.m. momentum, θ is the c.m. scattering angle, $a_\ell = (\eta_\ell e^{2i\delta_\ell} - 1)/2i$, $0 \le \eta_\ell \le 1$, and δ_ℓ is the phase shift of the ℓ^{th} partial wave. For purely elastic scattering, $\eta_\ell = 1$. The differential cross section is

$$\frac{d\sigma}{d\Omega} = |f(k,\theta)|^2 \ . \qquad (35.45)$$

The optical theorem states that

$$\sigma_{\mathrm{tot}} = \frac{4\pi}{k}\mathrm{Im}\, f(k,0) \ , \qquad (35.46)$$

and the cross section in the ℓ^{th} partial wave is therefore bounded:

$$\sigma_\ell = \frac{4\pi}{k^2}(2\ell + 1)|a_\ell|^2 \le \frac{4\pi(2\ell + 1)}{k^2} \ . \qquad (35.47)$$

The evolution with energy of a partial-wave amplitude a_ℓ can be displayed as a trajectory in an Argand plot, as shown in Fig. 35.6.

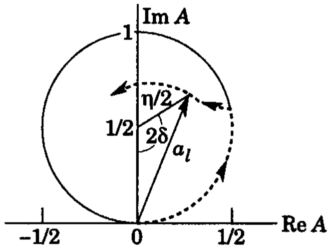


Figure 35.6: Argand plot showing a partial-wave amplitude a_ℓ as a function of energy. The amplitude leaves the unitary circle where inelasticity sets in ($\eta_\ell < 1$).

The usual Lorentz-invariant matrix element $\mathscr{M}$ (see Sec. 35.3 above) for the elastic process is related to $f(k,\theta)$ by

$$\mathscr{M} = -8\pi\sqrt{s}\, f(k,\theta) \ , \qquad (35.48)$$

so

$$\sigma_{\mathrm{tot}} = -\frac{1}{2p_{\mathrm{lab}}\, m_2}\,\mathrm{Im}\,\mathscr{M}(t = 0) \ , \qquad (35.49)$$

where s and t are the center-of-mass energy squared and momentum transfer squared, respectively (see Sec. 35.4.1).

35.5.3.1. *Resonances:* The Breit-Wigner (nonrelativistic) form for an elastic amplitude a_ℓ with a resonance at c.m. energy E_R, elastic width $\Gamma_{\rm el}$, and total width $\Gamma_{\rm tot}$ is

$$a_\ell = \frac{\Gamma_{\rm el}/2}{E_R - E - i\Gamma_{\rm tot}/2} \ , \tag{35.50}$$

where E is the c.m. energy. As shown in Fig. 35.7, in the absence of background the elastic amplitude traces a counterclockwise circle with center $ix_{\rm el}/2$ and radius $x_{\rm el}/2$, where the elasticity $x_{\rm el} = \Gamma_{\rm el}/\Gamma_{\rm tot}$. The amplitude has a pole at $E = E_R - i\Gamma_{\rm tot}/2$.

The spin-averaged Breit-Wigner cross section for a spin-J resonance produced in the collision of particles of spin S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{\pi}{k^2} \frac{B_{\rm in}B_{\rm out}\Gamma^2_{\rm tot}}{(E-E_R)^2 + \Gamma^2_{\rm tot}/4} \ , \tag{35.51}$$

where k is the c.m. momentum, E is the c.m. energy, and $B_{\rm in}$ and $B_{\rm out}$ are the branching fractions of the resonance into the entrance and exit channels. The $2S+1$ factors are the multiplicities of the incident spin states, and are replaced by 2 for photons. This expression is valid only for an isolated state. If the width is not small, $\Gamma_{\rm tot}$ cannot be treated as a constant independent of E. There are many other forms for σ_{BW}, all of which are equivalent to the one given here in the narrow-width case. Some of these forms may be more appropriate if the resonance is broad.

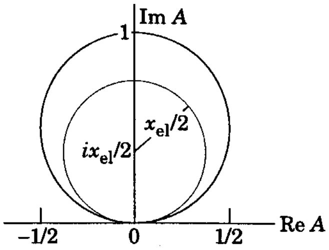


Figure 35.7: Argand plot for a resonance.

The relativistic Breit-Wigner form corresponding to Eq. (35.50) is:

$$a_\ell = \frac{-m\Gamma_{\rm el}}{s - m^2 + im\Gamma_{\rm tot}} \ . \tag{35.52}$$

A better form incorporates the known kinematic dependences, replacing $m\Gamma_{\rm tot}$ by $\sqrt{s}\,\Gamma_{\rm tot}(s)$, where $\Gamma_{\rm tot}(s)$ is the width the resonance particle would have if its mass were $\sqrt{s}$, and correspondingly $m\Gamma_{\rm el}$ by $\sqrt{s}\,\Gamma_{\rm el}(s)$ where $\Gamma_{\rm el}(s)$ is the partial width in the incident channel for a mass $\sqrt{s}$:

$$a_\ell = \frac{-\sqrt{s}\,\Gamma_{\rm el}(s)}{s - m^2 + i\sqrt{s}\,\Gamma_{\rm tot}(s)} \ . \tag{35.53}$$

For the Z boson, all the decays are to particles whose masses are small enough to be ignored, so on dimensional grounds $\Gamma_{\rm tot}(s) = \sqrt{s}\,\Gamma_0/m_Z$, where Γ_0 defines the width of the Z, and $\Gamma_{\rm el}(s)/\Gamma_{\rm tot}(s)$ is constant. A full treatment of the line shape requires consideration of dynamics, not just kinematics. For the Z this is done by calculating the radiative corrections in the Standard Model.

36. CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES

Revised April 1998 by R.N. Cahn (LBNL).

36.1. Leptoproduction

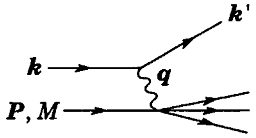


Figure 36.1: Kinematic quantities for description of lepton-nucleon scattering. k and k' are the four-momenta of incoming and outgoing leptons, P is the four-momentum of a nucleon with mass M. The exchanged particle is a γ, $W^\pm$, or Z^0; it transfers four-momentum $q = k - k'$ to the target.

Invariant quantities:

$\nu = \dfrac{q \cdot P}{M} = E - E'$ is the lepton's energy loss in the lab (in earlier literature sometimes $\nu = q \cdot P$). Here, E and E' are the initial and final lepton energies in the lab.

$Q^2 = -q^2 = 2(EE' - \overrightarrow{k} \cdot \overrightarrow{k}') - m_\ell^2 - m_{\ell'}^2$ where $m_\ell(m_{\ell'})$ is the initial (final) lepton mass. If $EE' \sin^2(\theta/2) \gg m_\ell^2, m_{\ell'}^2$, then

$\approx 4EE' \sin^2(\theta/2)$, where θ is the lepton's scattering angle in the lab.

$x = \dfrac{Q^2}{2M\nu}$ In the parton model, x is the fraction of the target nucleon's momentum carried by the struck quark. [See section on Quantum Chromodynamics (Sec. 9 of this *Review.*)]

$y = \dfrac{q \cdot P}{k \cdot P} = \dfrac{\nu}{E}$ is the fraction of the lepton's energy lost in the lab.

$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system recoiling against the lepton.

$s = (k + P)^2 = \dfrac{Q^2}{xy} + M^2$

36.1.1. *Leptoproduction cross sections*:

$$\begin{aligned}\frac{d^2\sigma}{dx\,dy} &= \nu\,(s - M^2)\,\frac{d^2\sigma}{d\nu\,dQ^2} = \frac{2\pi\,M\nu}{E'}\,\frac{d^2\sigma}{d\Omega_{\rm lab}\,dE'} \\ &= x(s - M^2)\,\frac{d^2\sigma}{dx\,dQ^2}\ . \end{aligned} \tag{36.1}$$

36.1.2. ***Leptoproduction structure functions***: The neutral-current process, $eN \to eX$, at low Q^2 is just electromagnetic and parity conserving. It can be written in terms of two structure functions $F_1^{\rm em}(x, Q^2)$ and $F_2^{\rm em}(x, Q^2)$:

$$\begin{aligned}\frac{d^2\sigma}{dx\,dy} &= \frac{4\pi\,\alpha^2(s - M^2)}{Q^4} \\ &\times \left[(1-y)\,F_2^{\rm em} + y^2\,xF_1^{\rm em} - \frac{M^2}{(s - M^2)}\,xy\,F_2^{\rm em}\right]\ . \end{aligned} \tag{36.2}$$

The charged-current processes, $e^-N \to \nu X$, $\nu N \to e^-X$, and $\overline{\nu}N \to e^+X$, are parity violating and can be written in terms of three structure functions $F_1^{\rm CC}(x, Q^2)$, $F_2^{\rm CC}(x, Q^2)$, and $F_3^{\rm CC}(x, Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\,(s - M^2)}{2\pi}\,\frac{M_W^4}{(Q^2 + M_W^2)^2} \tag{36.3}$$

$$\times\ \left\{\left[1 - y - \frac{M^2xy}{(s - M^2)}\right]F_2^{\rm CC} + \frac{y^2}{2}\,2x\,F_1^{\rm CC} \pm (y - \frac{y^2}{2})\,x\,F_3^{\rm CC}\right\}\ ,$$

where the last term is positive for the e^- and ν reactions and negative for $\overline{\nu}N \to e^+X$. As explained below there are different structure functions for charge-raising and charge-lowering currents.

36.1.3. ***Structure functions in the QCD parton model***: In the QCD parton model, the structure functions defined above can be expressed in terms of parton distribution functions. The quantity $f_i(x, Q^2)dx$ is the probability that a parton of type i (quark, antiquark, or gluon), carries a momentum fraction between x and $x + dx$ of the nucleon's momentum in a frame where the nucleon's momentum is large. For the cross section corresponding to the *neutral-current process* $ep \to eX$, we have for $s \gg M^2$ (in the case where the incoming electron is either left- (L) or right- (R) handed):

$$\begin{aligned}\frac{d^2\sigma}{dx\,dy} &= \frac{\pi\alpha^2}{sx^2\,y^2}\left[\sum_q \left(x\,f_q\,(x,\,Q^2) + x\,f_{\overline{q}}\,(x,\,Q^2)\right)\right] \\ &\times \left[A_q + (1-y)^2\,B_q\right]\ . \end{aligned} \tag{36.4}$$

Here the index q refers to a quark flavor (*i.e.*, u, d, s, c, b, or t), and

$$A_q = \left(-q_q + g_{Lq}\,g_{Le}\,\frac{Q^2}{Q^2 + M_Z^2}\right)^2 + \left(-q_q + g_{Rq}\,g_{Re}\,\frac{Q^2}{Q^2 + M_Z^2}\right)^2 , \tag{36.5}$$

$$B_q = \left(-q_q + g_{Rq}\,g_{Le}\,\frac{Q^2}{Q^2 + M_Z^2}\right)^2 + \left(-q_q + g_{Lq}\,g_{Re}\,\frac{Q^2}{Q^2 + M_Z^2}\right)^2 . \tag{36.6}$$

Here q_q is the charge of flavor q. For a left-handed electron, $g_{Re} = 0$ and $g_{Le} = (-1/2 + \sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, while for a right-handed electron, $g_{Le} = 0$ and $g_{Re} = (\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$. For the quarks, $g_{Lq} = (T_3 - q_q\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, and $g_{Rq} = (-q_q\sin^2\theta_W)\ /\ (\sin\theta_W\cos\theta_W)$.

For neutral-current *neutrino* (*antineutrino*) *scattering*, the same formula applies with g_{Le} replaced by $g_{L\nu} = 1/(2\sin\theta_W\cos\theta_W)$ ($g_{L\overline{\nu}}$ $= 0$) and g_{Re} replaced by $g_{R\nu} = 0$ [$g_{R\overline{\nu}} = -1/(2\sin\theta_W\cos\theta_W)$].

In the case of the *charged-current processes* $e_L^-p \to \nu X$ and $\overline{\nu}p \to e^+X$, Eq. (36.3) applies with

$$\begin{aligned}F_2 = 2xF_1 &= 2x\Big[f_u(x,Q^2) + f_c(x,Q^2) + f_t(x,Q^2) \\ &+\ f_{\overline{d}}\,(x,Q^2) + f_{\overline{s}}\,(x,Q^2) + f_{\overline{b}}\,(x,Q^2)\Big]\ , \end{aligned} \tag{36.7}$$

$$\begin{aligned}F_3 &= 2\Big[f_u(x,Q^2) + f_c(x,Q^2) + f_t(x,Q^2) \\ &-\ f_{\overline{d}}\,(x,Q^2) - f_{\overline{s}}\,(x,Q^2) - f_{\overline{b}}\,(x,Q^2)\Big]\ . \end{aligned} \tag{36.8}$$

For the process $\nu p \to e^-X$:

$$\begin{aligned}F_2 = 2xF_1 &= 2x\Big[f_d(x,Q^2) + f_s(x,Q^2) + f_b(x,Q^2) \\ &+\ f_{\overline{u}}\,(x,Q^2) + f_{\overline{c}}\,(x,Q^2) + f_{\overline{t}}\,(x,Q^2)\Big]\ , \end{aligned} \tag{36.9}$$

$$\begin{aligned}F_3 &= 2\Big[f_d(x,Q^2) + f_s(x,Q^2) + f_b(x,Q^2) \\ &-\ f_{\overline{u}}\,(x,Q^2) - f_{\overline{c}}\,(x,Q^2) - f_{\overline{t}}\,(x,Q^2)\Big]\ . \end{aligned} \tag{36.10}$$

36.2. e^+e^- annihilation

For pointlike, spin-1/2 fermions, the differential cross section in the c.m. for $e^+e^- \to f\overline{f}$ via single photon annihilation is (θ is the angle between the incident electron and the produced fermion; $N_c = 1$ if f is a lepton and $N_c = 3$ if f is a quark).

$$\frac{d\sigma}{d\Omega} = N_c\frac{\alpha^2}{4s}\beta[1 + \cos^2\theta + (1 - \beta^2)\sin^2\theta]\,Q_f^2\ , \tag{36.11}$$

where β is the velocity of the final state fermion in the c.m. and Q_f is the charge of the fermion in units of the proton charge. For $\beta \to 1$,

$$\sigma = N_c\frac{4\pi\alpha^2}{3s}Q_f^2 = N_c\frac{86.8Q_f^2\ nb}{s(GeV/c^2)}\ . \tag{36.12}$$

At higher energies, the Z^0 (mass M_Z and width Γ_Z) must be included. If the mass of a fermion f is much less than the mass of the Z^0, then the differential cross section for $e^+e^- \rightarrow f\overline{f}$ is

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \; & N_c\frac{\alpha^2}{4s}\left\{(1+\cos^2\theta)\left[Q_f^2 - 2\chi_1 v_e v_f Q_f + \chi_2(a_e^2+v_e^2)(a_f^2+v_f^2)\right]\right.\\ & \left. + 2\cos\theta\left[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f\right]\right\} \qquad (36.13)\end{aligned}$$

where

$$\begin{aligned}\chi_1 = \; & \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} \;,\\ \chi_2 = \; & \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} \;,\\ a_e = \; & -1 \;,\\ v_e = \; & -1+4\sin^2\theta_W \;,\\ a_f = \; & 2T_{3f} \;,\\ v_f = \; & 2T_{3f} - 4Q_f\sin^2\theta_W \;, \qquad (36.14)\end{aligned}$$

where $T_{3f} = 1/2$ for u, c and neutrinos, while $T_{3f} = -1/2$ for d, s, b, and negatively charged leptons.

At LEP II it may be possible to produce the orthodox Higgs boson, H, (see the mini-review on Higgs bosons) in the reaction $e^+e^- \rightarrow HZ^0$, which proceeds dominantly through a virtual Z^0. The Standard Model prediction for the cross section [3] is

$$\sigma(e^+e^- \rightarrow HZ^0) = \frac{\pi\alpha^2}{24}\cdot\frac{2K}{\sqrt{s}}\cdot\frac{K^2+3M_Z^2}{(s-M_Z^2)^2}\cdot\frac{1-4\sin^2\theta_W+8\sin^4\theta_W}{\sin^4\theta_W\cos^4\theta_W} \;. \qquad (36.15)$$

where K is the c.m. momentum of the produced H or Z^0. Near the production threshold, this formula needs to be corrected for the finite width of the Z^0.

36.3. Two-photon process at e^+e^- colliders

When an e^+ and an e^- collide with energies E_1 and E_2, they emit dn_1 and dn_2 virtual photons with energies ω_1 and ω_2 and 4-momenta q_1 and q_2. In the equivalent photon approximation, the cross section for $e^+e^- \rightarrow e^+e^-X$ is related to the cross section for $\gamma\gamma \rightarrow X$ by (Ref. 1)

$$d\sigma_{e^+e^-\rightarrow e^+e^-X}\,(s) = dn_1\,dn_2\,d\sigma_{\gamma\gamma\rightarrow X}\,(W^2) \qquad (36.16)$$

where $s = 4E_1E_2$, $W^2 = 4\omega_1\omega_2$ and

$$dn_i = \frac{\alpha}{\pi}\left[1 - \frac{\omega_i}{E_i} + \frac{\omega_i^2}{2E_i^2} - \frac{m_e^2\omega_i^2}{(-q_i^2)E_i^2}\right]\frac{d\omega_i}{\omega_i}\,\frac{d(-q_i^2)}{(-q_i^2)} \;. \qquad (36.17)$$

After integration (including that over q_i^2 in the region $m_e^2\omega_i^2/E_i(E_i-\omega_i) \le -q_i^2 \le (-q^2)_{\rm max}$), the cross section is

$$\begin{aligned}\sigma_{e^+e^-\rightarrow e^+e^-X}\,(s) = & \frac{\alpha^2}{\pi^2}\int_{z_{th}}^1\frac{dz}{z}\left[f(z)\left(\ln\frac{(-q^2)_{\rm max}}{m_e^2 z} - 1\right)^2\right.\\ & \left. - \tfrac{1}{3}\left(\ln\frac{1}{z}\right)^3\right]\sigma_{\gamma\gamma\rightarrow X}\,(zs) \;;\\ f(z) = & \left(1+\tfrac{1}{2}z\right)^2\ln\frac{1}{z} - \tfrac{1}{2}(1-z)(3+z) \;;\\ z = & \frac{W^2}{s} \;. \qquad (36.18)\end{aligned}$$

The quantity $(-q^2)_{\rm max}$ depends on properties of the produced system X, in particular, $(-q^2)_{\rm max} \sim m_\rho^2$ for hadron production ($X = h$) and $(-q^2)_{\rm max} \sim W^2$ for lepton pair production ($X = \ell^+\ell^-$, $\ell = e, \mu, \tau$).

For production of a resonance of mass m_R and spin $J \neq 1$

$$\begin{aligned}\sigma_{e^+e^-\rightarrow e^+e^-R}\,(s) = & (2J+1)\frac{8\alpha^2\Gamma_{R\rightarrow\gamma\gamma}}{m_R^3}\\ \times & \left[f(m_R^2/s)\left(\ln\frac{sm_V^2}{m_e^2m_R^2} - 1\right)^2 - \frac{1}{3}\left(\ln\frac{s}{m_R^2}\right)^3\right] \qquad (36.19)\end{aligned}$$

where m_V is the mass that enters into the form factor of the $\gamma\gamma \rightarrow R$ transition: $m_V \sim m_\rho$ for $R = \pi^0, \rho^0, \omega, \phi, \ldots$, $m_V \sim m_R$ for $R = c\overline{c}$ or $b\overline{b}$ resonances.

36.4. Inclusive hadronic reactions

One-particle inclusive cross sections $Ed^3\sigma/d^3p$ for the production of a particle of momentum p are conveniently expressed in terms of rapidity (see above) and the momentum p_T transverse to the beam direction (defined in the center-of-mass frame)

$$E\frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi\,dy\,p_T\,dp_T} \;. \qquad (36.20)$$

In the case of processes where p_T is large or the mass of the produced particle is large (here large means greater than 10 GeV), the parton model can be used to calculate the rate. Symbolically

$$\sigma_{\rm hadronic} = \sum_{ij}\int f_i(x_1,\,Q^2)\,f_j(x_2,\,Q^2)\,dx_1\,dx_2\,\widehat{\sigma}_{\rm partonic} \;, \qquad (36.21)$$

where $f_i(x,\,Q^2)$ is the parton distribution introduced above and Q is a typical momentum transfer in the partonic process and $\widehat{\sigma}$ is the partonic cross section. Some examples will help to clarify. The production of a W^+ in pp reactions at rapidity y in the center-of-mass frame is given by

$$\begin{aligned}\frac{d\sigma}{dy} = & \frac{G_F\,\pi\sqrt{2}}{3}\\ & \times\tau\left[\cos^2\theta_c\left(u(x_1\,,\,M_W^2)\,\overline{d}\,(x_2,M_W^2)\right.\right.\\ & \qquad \left. + \, u(x_2\,,\,M_W^2)\,\overline{d}\,(x_1,M_W^2)\right)\\ & \quad + \, \sin^2\theta_c\left(u(x_1\,,\,M_W^2)\,\overline{s}\,(x_2\,,\,M_W^2)\right.\\ & \qquad \left.\left. + \, s(x_2,M_W^2)\,\overline{u}\,(x_1,M_W^2)\right)\right] \;, \qquad (36.22)\end{aligned}$$

where $x_1 = \sqrt{\tau}\,e^y$, $x_2 = \sqrt{\tau}\,e^{-y}$, and $\tau = M_W^2/s$. Similarly the production of a jet in pp (or $p\overline{p}$) collisions is given by

$$\begin{aligned}\frac{d^3\sigma}{d^2p_T\,dy} = & \sum_{ij}\int f_i(x_1\,,\,p_T^2)\,f_j(x_2,p_T^2)\\ & \times\left[\widehat{s}\,\frac{d\widehat{\sigma}}{d\,\widehat{t}}\right]_{ij}\,dx_1\,dx_2\,\delta(\,\widehat{s} + \widehat{t} + \widehat{u}) \;, \qquad (36.23)\end{aligned}$$

where the summation is over quarks, gluons, and antiquarks. Here

$$\begin{aligned}s = & (p_1+p_2)^2 \;, \qquad (36.24)\\ t = & (p_1-p_{\rm jet})^2 \;, \qquad (36.25)\\ u = & (p_2-p_{\rm jet})^2 \;, \qquad (36.26)\end{aligned}$$

p_1 and p_2 are the momenta of the incoming p and p (or $\overline{p}$) and $\widehat{s}$, $\widehat{t}$, and $\widehat{u}$ are s, t, and u with $p_1 \rightarrow x_1p_1$ and $p_2 \rightarrow x_2\,p_2$. The partonic cross section $\widehat{s}\,[(d\widehat{\sigma})/(d\,\widehat{t}\,)]$ can be found in Ref. 2. Example: for the process $gg \rightarrow q\overline{q}$,

$$\widehat{s}\,\frac{d\sigma}{dt} = 3\alpha_s^2\,\frac{(\,\widehat{t}^{\,2}+\widehat{u}^2)}{8\widehat{s}}\,\left[\frac{4}{9\,\widehat{t}\,\widehat{u}} - \frac{1}{\widehat{s}^{\,2}}\right] \;. \qquad (36.27)$$

The prediction of Eq. (36.23) is compared to data from the UA1 and UA2 collaborations in Fig. 38.8 in the Plots of Cross Sections and Related Quantities section of this *Review*.

The associated production of a Higgs boson and a gauge boson is analogous to the process $e^+e^- \rightarrow HZ^0$ in Sec. 36.2. The required parton-level cross sections [4], averaged over initial quark colors, are

$$\begin{aligned}\sigma(q_i\overline{q}_j \rightarrow W^\pm H) = \; & \frac{\pi\alpha^2|V_{ij}|^2}{36\sin^4\theta_W}\cdot\frac{2K}{\sqrt{s}}\cdot\frac{K^2+3M_W^2}{(s-M_W^2)^2}\\ \sigma(q\overline{q} \rightarrow Z^0H) = \; & \frac{\pi\alpha^2(a_q^2+v_q^2)}{144\sin^4\theta_W\cos^4\theta_W}\cdot\frac{2K}{\sqrt{s}}\cdot\frac{K^2+3M_Z^2}{(s-M_Z^2)^2} \;.\end{aligned}$$

Here V_{ij} is the appropriate element of the Kobayashi-Maskawa matrix and K is the c.m. momentum of the produced H. The axial and vector couplings are defined as in Sec. 36.2.

36.5. One-particle inclusive distributions

In order to describe one-particle inclusive production in e^+e^- annihilation or deep inelastic scattering, it is convenient to introduce a fragmentation function $D_i^h\,(z,Q^2)$ where $D_i^h\,(z,Q^2)$ is the number of hadrons of type h and momentum between zp and $(z+dz)p$ produced in the fragmentation of a parton of type i. The Q^2 evolution is predicted by QCD and is similar to that of the parton distribution functions [see section on Quantum Chromodynamics (Sec. 9 of this *Review*)]. The $D_i^h(z,Q^2)$ are normalized so that

$$\sum_h \int zD_i^h\,(z,Q^2)dz = 1\ . \qquad (36.28)$$

If the contributions of the Z boson and three-jet events are neglected, the cross section for producing a hadron h in e^+e^- annihilation is given by

$$\frac{1}{\sigma_{\rm had}}\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\, D_i^h\,(z,Q^2)}{\sum_i e_i^2}\ , \qquad (36.29)$$

where e_i is the charge of quark-type i, $\sigma_{\rm had}$ is the total hadronic cross section, and the momentum of the hadron is $zE_{\rm cm}/2$.

In the case of deep inelastic muon scattering, the cross section for producing a hadron of energy E_h is given by

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\, q_i(x,Q^2)\, D_i^h(z,Q^2)}{\sum_i e_i^2\, q_i(x,Q^2)}\ , \qquad (36.30)$$

where $E_h = \nu z$. (For the kinematics of deep inelastic scattering, see Sec. 35.4.2 of the Kinematics section of this *Review*.) The fragmentation functions for light and heavy quarks have a different z dependence; the former peak near $z = 0$. They are illustrated in Figs. 37.1 and 37.2 in the section on "Heavy Quark Fragmentation in e^+e^- Annihilation" (Sec. 37 of this *Review*).

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37. HEAVY-QUARK FRAGMENTATION IN e^+e^- ANNIHILATION

Written January 1998 by D. Besson (University of Kansas).

Measurement of the fragmentation functions of heavy quarks provides information about non-perturbative particle production in a variety of experimental environments. The CDF observation of high p_T $J/\psi(1S)$ production rates far in excess of the extant theoretical predictions prompted the development of the color octet model (*e.g.*, $p\bar{p} \to gg \to \chi_c \to \psi + \mathrm{X}$) and highlighted the role of gluon fragmentation in charmonium production. Recent results from both LEP and HERA have also helped elucidate the gluonic contribution to charmed meson production. Current estimates from LEP are that gluon fragmentation accounts for approximately half of the D^* production in the lowest momentum region (the lowest quarter of the allowed kinematic region).

Many functional forms have been suggested to describe these momentum spectra for heavy quarks produced in e^+e^- annihilations. The functional form given by Peterson *et al.* [1] in terms of just one free parameter ϵ_P has found widespread use; other parameterizations are also given in the literature [2]. The earliest Peterson form was a function of one variable z, defined for a heavy-quark Q, light-quark $\bar{q}$ system as the ratio of the energy plus the longitudinal momentum of the hadron $Q\bar{q}$ to the sum of the energy and momentum of the heavy quark after accounting for initial state radiation, gluon bremsstrahlung, and final state radiation: $z = (E + p_{\|})_{Q\bar{q}}/(E + p_Q)$. The main advantage of this variable is that it is relativistically invariant with respect to boosts in the direction of the primary quark. Unfortunately, as this quantity is not directly accessible, experiments typically use other scaling variables which are close approximations to z—either $x^+ = (p_{\|} + E)_{\mathrm{hadron}}/(p_{\|} + E)_{\mathrm{max}}$, $x_p = p/p_{\mathrm{max}}$, or $x_E = E_{\mathrm{hadron}}/E_{\mathrm{beam}}$.

The Peterson functional form is:

$$\frac{dN}{dz} = \frac{1}{z[1 - (1/z) - \epsilon_P/(1-z)]^2} \tag{37.1}$$

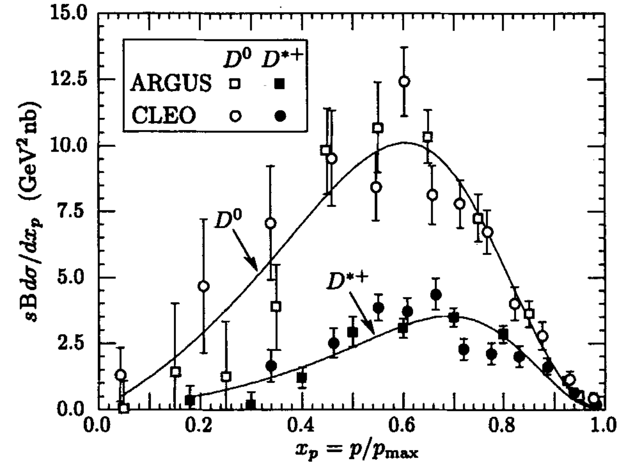

Figure 37.1: Efficiency-corrected inclusive cross section measurements for the production of D^0 and D^{*+} in e^+e^- measurements at $\sqrt{s} \approx 10$ GeV. The variable x_p is related to the Peterson variable z, but is not identical to it.

The bulk of the available fragmentation function data on charmed mesons (excluding $J/\psi(1S)$) is from measurements at $\sqrt{s} = 10$ GeV. Shown in Fig. 37.1 are the efficiency-corrected (but not branching ratio corrected) CLEO [3] and ARGUS [4] inclusive cross sections ($s \cdot Bd\sigma/dx_p$ in units of GeV^2-nb, with $x_p = p/p_{\mathrm{max}}$) for the production of pseudoscalar D^0 and vector D^{*+} in e^+e^- annihilations at $\sqrt{s} \approx 10$ GeV. For the D^0, B represents the branching fraction for $D^0 \to K^-\pi^+$; for the D^{*+}, B represents the product branching fraction: $D^{*+} \to D^0\pi^+; D^0 \to K^-\pi^+$. These inclusive spectra have not been corrected for cascades from higher states, nor for radiative effects. Note that since the momentum spectra are sensitive to radiative corrections, comparison of charm spectra at $\sqrt{s} = 10$ GeV cannot be compared directly with spectra at higher center-of-mass energies, and must be appropriately evolved.

Fits to the combined CLEO and ARGUS D^0 and D^{*+} data give $\epsilon_P(D^0) = 0.135 \pm 0.01$ and $\epsilon_P(D^*) = 0.078 \pm 0.008$; these are indicated in the solid curves. Measurement of the fragmentation functions for a variety of particles has allowed comparisons between mesons and baryons, and particles of different spin structure, as shown in Table 37.1

Table 37.1: The Peterson momentum hardness parameter ϵ_P as obtained from $e^+e^- \to$ (particle) + X measurements.

Particle	L	$\sqrt{s}$	ϵ_P	Reference
D^0	0	10 GeV	0.135 ± 0.01	[3]
D^{*+}	0	10 GeV	0.078 ± 0.008	[3]
D_s^*	0	10 GeV	$0.04^{+0.03}_{-0.01}$	[5]
$D_1^0(2420)$	1	10 GeV	$0.034^{+0.018}_{-0.012}$	[6]
$D_2^0(2460)$	1	10 GeV	0.015 ± 0.004	[6]
$D_1^+(2420)$	1	10 GeV	$0.020^{+0.011}_{-0.006}$	[7]
$D_2^+(2460)$	1	10 GeV	0.013 ± 0.007	[7]
$D_{s1}(2536)$	1	10 GeV	$0.06^{+0.035}_{-0.03}$	[8]
$D_{s2}(2573)$	1	10 GeV	$0.027^{+0.043}_{-0.016}$	[9]
Λ_c	0	10 GeV	0.25 ± 0.03	[10,11]
Ξ_c	0	10 GeV	0.23 ± 0.05	[12,13]
Σ_c	0	10 GeV	0.29 ± 0.06	[14,15]
Σ_c^*	0	10 GeV	$0.30^{+0.10}_{-0.07}$	[16]
Ξ_c^{*+}	0	10 GeV	$0.24^{+0.22}_{-0.10}$	[17]
Ξ_c^{*0}	0	10 GeV	$0.22^{+0.15}_{-0.08}$	[18]
$\Lambda_{c,1}$	1	10 GeV	0.059 ± 0.028	[19,20]
$\Lambda_{c,2}$	1	10 GeV	0.053 ± 0.012	[19,21]
$\Xi_{c,2}$	1	10 GeV	$0.058^{+0.037}_{-0.021}$	[22]
b hadrons	—	90 GeV	$0.0047^{+0.0010}_{-0.0008}$	[23]

We note from Table 37.1 that the mass dependence of ϵ_P is less marked than the dependence on the orbital angular momentum structure of the charmed hadron being measured. Orbitally excited $L = 1$ charmed hadrons (D_J, $D_{s,J}$, and $\Lambda_{c,J}$) show consistently harder spectra (*i.e.*, smaller values of ϵ_P) than the $L = 0$ ground states, whereas the data for the ground state charmed baryons Λ_c and Ξ_c show agreement with the lighter (by ≈ 400–600 MeV) ground-state D and D_s charmed mesons. To some extent, the harder spectra of $L = 1$ hadrons can be attributed to the fact that all the $L = 1$ charmed hadrons will eventually decay into $L = 0$ hadrons.

Bottom-flavored hadrons at LEP have been measured to have an even harder momentum spectrum than charmed hadrons at lower energies [23–25]. Qualitatively, whereas charm spectra peak at $x_p \approx 0.6$, the spectra of bottom hadrons peak at $x_p \approx 0.8$. This is as expected in the Peterson model, where the value ϵ_P is expected to vary as the ratio of the effective light quark mass to the heavy quark mass in a heavy quark + light (di)quark hadron. In the case of charm, the Peterson functional form provides an acceptable description of the shape of the x_p distribution, provided the appropriate ϵ_P value is independently determined for each separate species of charmed particle. However, unlike charm, the numbers of fully reconstructed b-flavored hadrons is too small to allow a statistically compelling measure of ϵ_P for each separate bottom hadron. Consequently, a b-enriched sample is isolated kinematically, using, *e.g.*, a high p_T lepton and/or a displaced vertex to tag a primary b quark. The x_p distribution therefore includes all b-flavored hadrons in the sample, and does not yet allow a straightforward species-by-species ϵ_P extraction. Additional uncertainties in the case of bottom arise from the sensitivity of ϵ_P to the fragmentation model used to non-perturbatively evolve the initial $q\overline{q}$ system into final state hadrons.

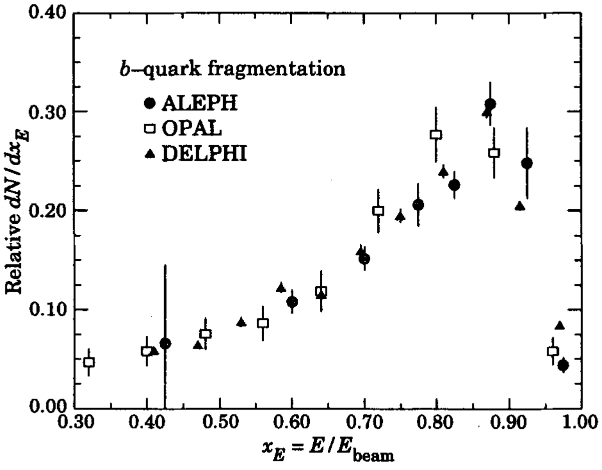

Figure 37.2: Fractional energy distribution for b-quark fragmentation for inclusive b production at LEP.

In general, the b-quark fragmentation function distribution is found to be somewhat narrower than the shape of the Peterson function; this may be due to a systematic underestimate of soft gluon emission in event generators, and/or uncertainties in the appropriate mix of b-flavored hadrons. The match of a single Peterson function to data is therefore much more difficult for bottom than charm at this time, although there is relatively good agreement from experiment to experiment, as seen in Fig. 37.2, which displays the fragmentation function data from OPAL [23], ALEPH [24], and DELPHI [25].

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38. PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES

NOTE: THE FIGURES IN THIS SECTION ARE INTENDED TO SHOW THE REPRESENTATIVE DATA.
THEY ARE NOT MEANT TO BE COMPLETE COMPILATIONS OF ALL THE WORLD'S RELIABLE DATA.

Structure Functions

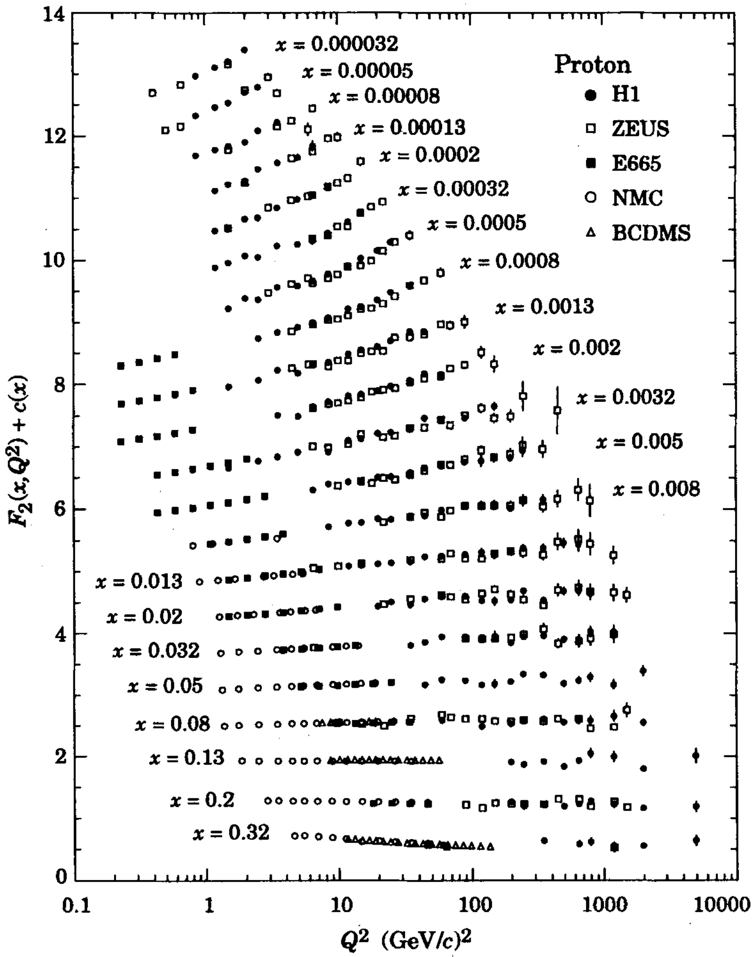


Figure 38.1: The proton structure function F_2^p measured in electromagnetic scattering of electrons (H1, ZEUS) and muons (BCDMS, E665, NMC), in the kinematic domain of the HERA data, for $x > 0.00003$; *cf.* Fig. 38.2 for data at smaller x. Only statistical errors are shown. The data are plotted as a function of Q^2 in bins of fixed x. The H1 binning in x is used in this plot; the ZEUS, BCDMS, E665 and NMC data are rebinned to the x values of the H1 data using a phenomenological parametrization. For the purpose of plotting, a constant $c(x) = 0.6(i_x - 0.4)$ is added to F_2^p, where i_x is the number of the x bin ranging from $i_x = 1$ ($x = 0.32$) to $i_x = 21$ ($x = 0.000032$). References: **H1**—S. Aid *et al.*, Nucl. Phys. **B470**, 3 (1996); C. Adloff *et al.*, Nucl. Phys. **B497**, 3 (1997); **ZEUS**—M. Derrick *et al.*, Z. Phys. **C72**, 399 (1996); J. Breitweg *et al.*, Phys. Lett. **B407**, 432 (1997); **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989); **E665**—M.R. Adams *et al.*, Phys. Rev. **D54**, 3006 (1996); **NMC**—M. Arneodo *et al.*, Phys. Lett. **B364**, 107 (1995). (Courtesy of R. Voss, 1997.)

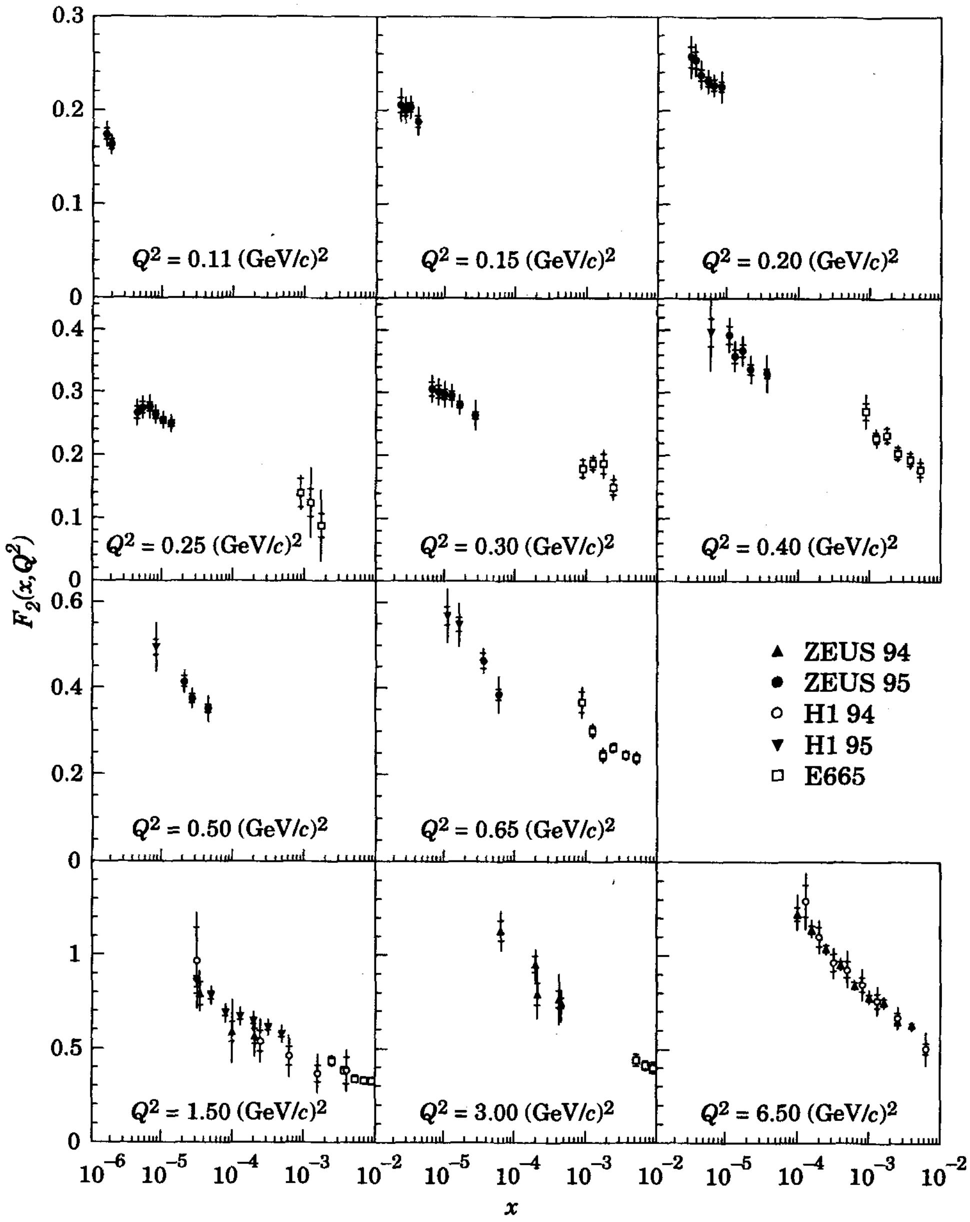


Figure 38.2: The proton structure function F_2^p at small x and Q^2, measured in electromagnetic scattering of electrons (H1, ZEUS) and muons (E665). The data are plotted as a function of x in bins of fixed Q^2. References: **ZEUS 94**—M. Derrick *et al.*, Z. Phys. **C72**, 399 (1996); **ZEUS 95**—J. Breitweg *et al.*, Phys. Lett. **B407**, 432 (1997); **H1 94**—S. Aid *et al.*, Nucl. Phys. **B470**, 3 (1996); **H1 95**—C. Adloff *et al.*, Nucl. Phys. **B497**, 3 (1997); **E665**—M.R. Adams *et al.*, Phys. Rev. **D54**, 3006 (1996). (Courtesy of R. Voss, 1997.)

Structure Functions

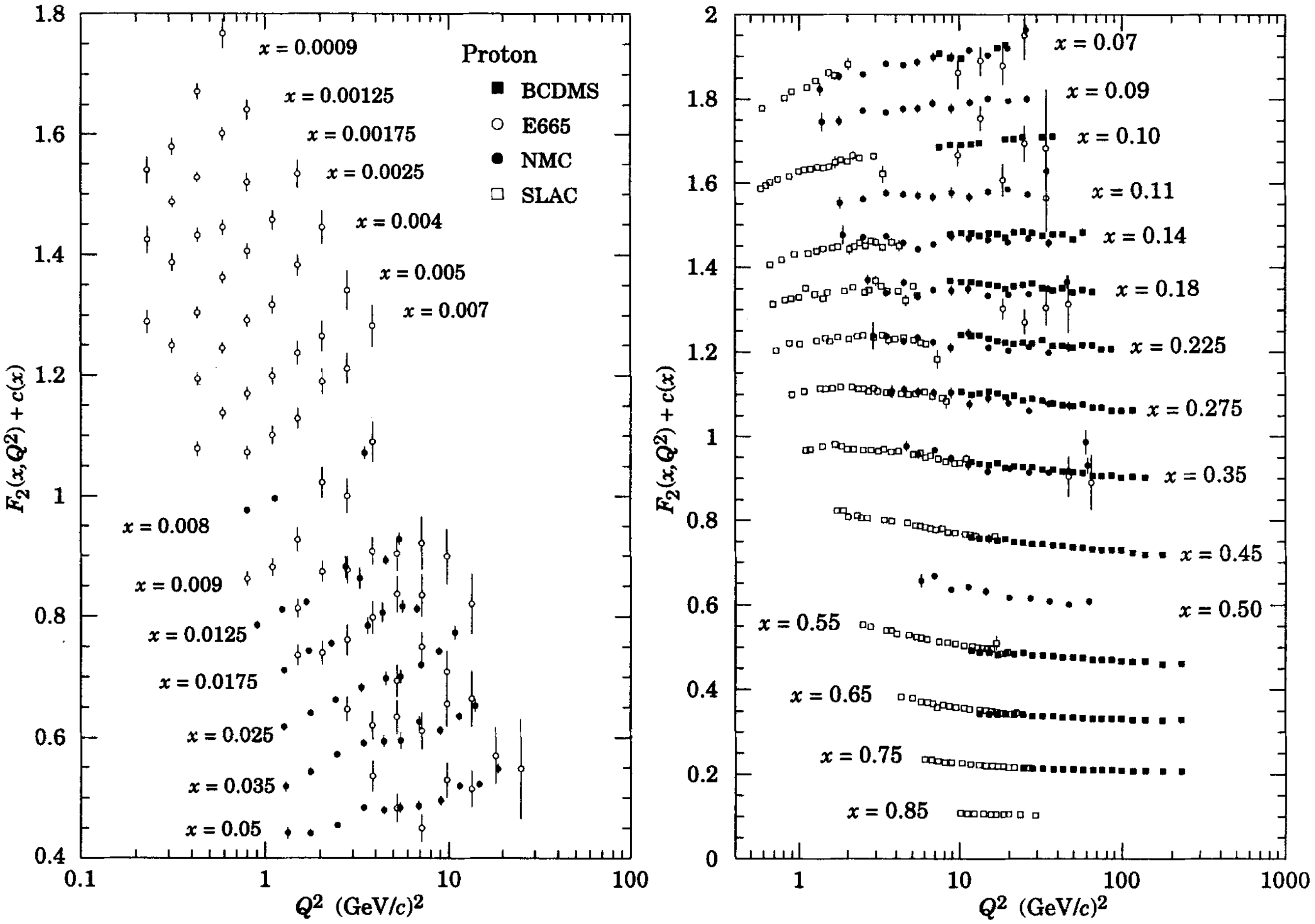


Figure 38.3: The proton structure function F_2^p measured in electromagnetic scattering of electrons (SLAC) and muons (BCDMS, E665, NMC), shown as a function of Q^2 for bins of fixed x. Only statistical errors are shown. For the purpose of plotting, a constant $c(x) = 0.1 i_x$ is added to F_2^p where i_x is the number of the x bin, ranging from 1 ($x = 0.05$) to 14 ($x = 0.0009$) on the left-hand figure, and from 1 ($x = 0.85$) to 15 ($x = 0.07$) on the right-hand figure. For HERA data in the kinematic range of this figure, see Fig. 38.1. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989); **E665**—M.R. Adams *et al.*, Phys. Rev. **D54**, 3006 (1996); **NMC**—M. Arneodo *et al.*, Phys. Lett. **B364**, 107 (1995). **SLAC**—L.W. Whitlow *et al.*, Phys. Lett. **B282**, 475 (1992). (Courtesy of R. Voss, 1996.)

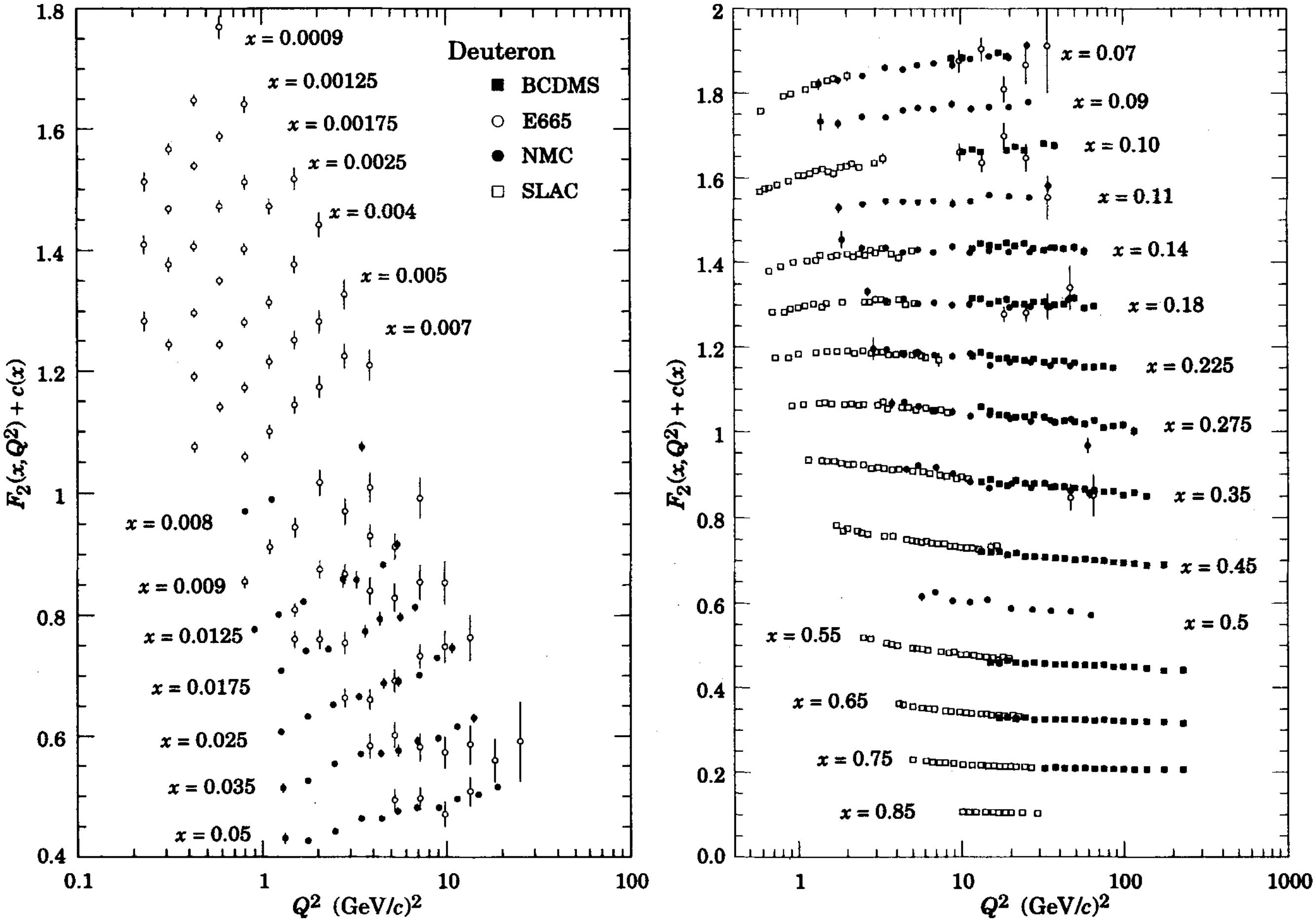

Structure Functions

Figure 38.4: As Fig. 38.3, for the deuteron structure function F_2^d. References: BCDMS—A.C. Benvenuti *et al.*, Phys. Lett. **B237**, 592 (1990). **E665, NMC, SLAC**—same references as Fig. 38.3. (Courtesy of R. Voss, 1996.)

Structure Functions

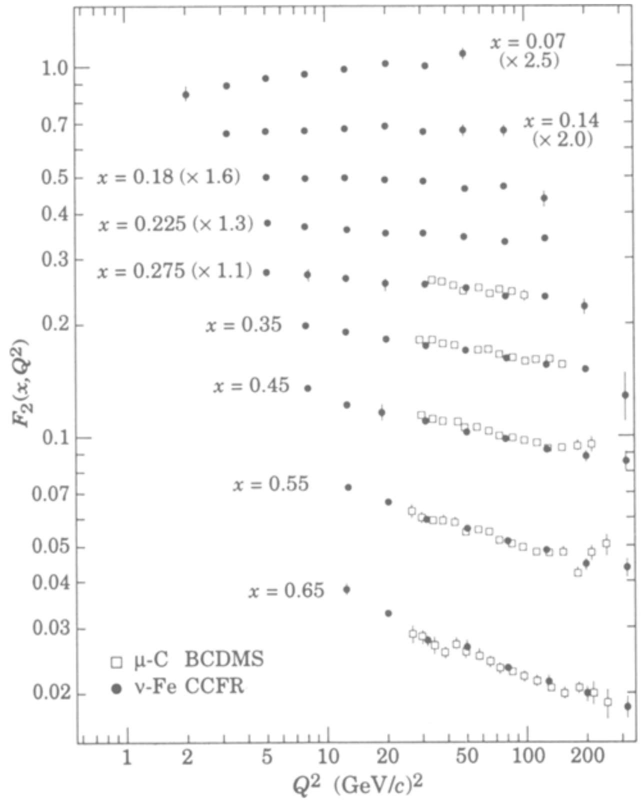


Figure 38.5: The nucleon structure function F_2 measured in deep inelastic scattering of muons on carbon (BCDMS) and neutrinos on iron (CCFR). The data are shown versus Q^2, for bins of fixed x, and have been scaled by the factors shown in parentheses. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **CCFR**—S.R. Mishra *et al.*, NEVIS-1465 (1992). (Courtesy of R. Voss, 1996.)

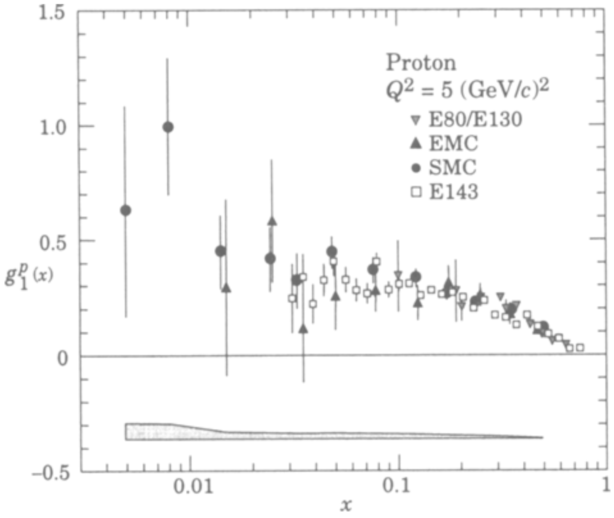


Figure 38.6: The spin-dependent structure function $g_1(x)$ of the proton measured in deep inelastic scattering of polarized electrons (E80, E130, E143) and muons (EMC, SMC), shown at $Q^2 = 5$ GeV^2. Only statistical errors are shown with the data points. As an example, the SMC systematic error is indicated by the shaded area. References: **E80**—M.J. Alguard *et al.*, Phys. Rev. Lett. **37**, 1261 (1976); ibid. **41**, 70 (1978); **E130**—G. Baum *et al.*, Phys. Rev. Lett. **51**, 1135 (1983); **E143**—K. Abe *et al.*, Phys. Rev. Lett. **74**, 346 (1995); **EMC**—J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1989); **SMC**—B. Adeva *et al.*, Phys. Lett. **B412**, 414 (1997). In this plot, the E80, E130 and EMC data have been reevaluated using up-to-date parametrizations of F_2^p and $R = \sigma_L/\sigma_T$. (Courtesy of R. Voss, 1997.)

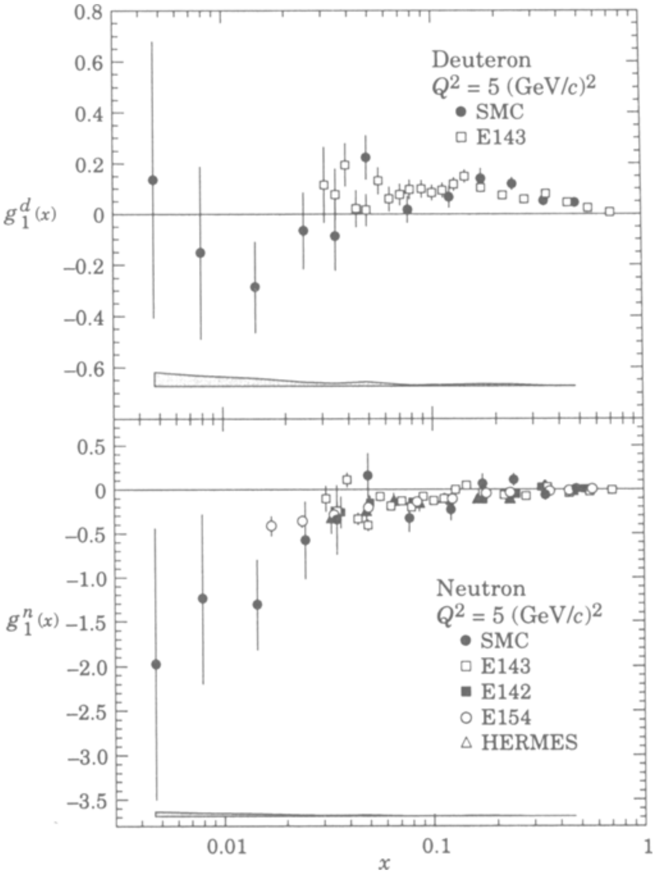
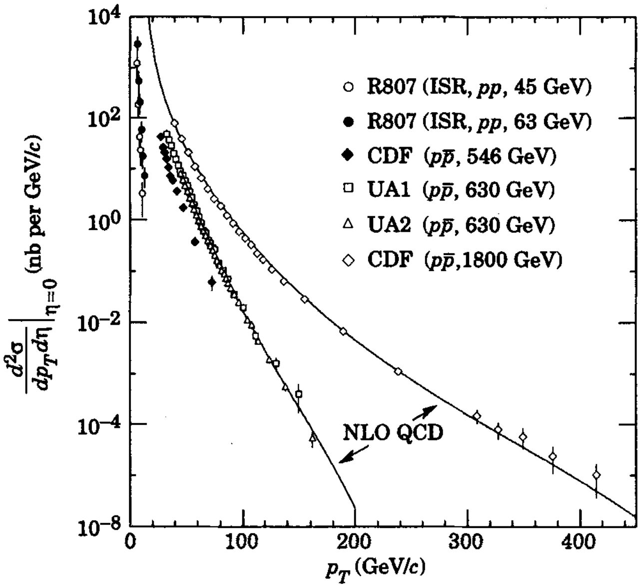
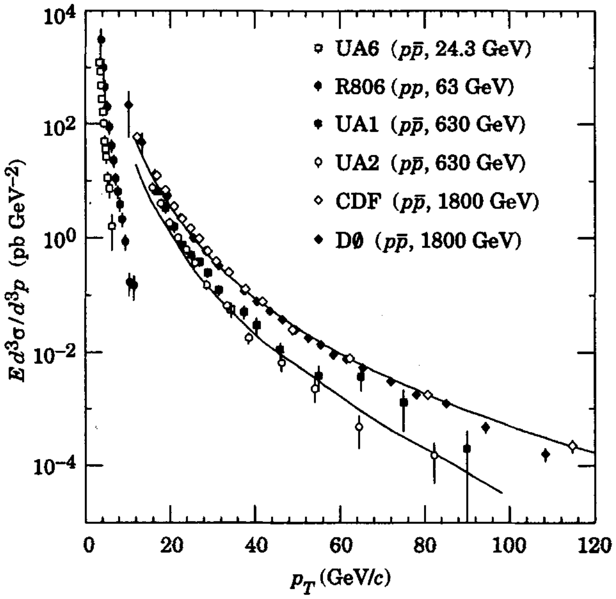


Figure 38.7: The spin-dependent structure function $g_1(x)$ of the deuteron (top) and the neutron (bottom) measured in deep inelastic scattering of polarized electrons (E142, E143, E154, HERMES) and muons (SMC). The SMC and E143 results for the neutron are evaluated from the difference of deuteron and proton data; the E142, E154, and HERMES results were obtained with polarized ^{3}He targets. Only statistical errors are shown with the data points. As an example, the SMC systematic error is indicated by the shaded area. All results except the HERMES data are shown at $Q^2 = 5$ GeV^2; the HERMES results are shown at the average Q^2 of the respective data point which varies from $Q^2 = 1.22$ GeV^2 at $x = 0.033$ to $Q^2 = 5.25$ GeV^2 at $x = 0.464$. References: **E142**—P.L. Anthony *et al.*, Phys. Rev. Lett. **71**, 959 (1993); **E143**-K. Abe *et al.*, Phys. Rev. Lett. **75**, 25 (1995); **E154**—K. Abe *et al.*, Phys. Lett. **B405**, 180 (1997) and hep-ph/9705344 v2 (1997); **HERMES**—K. Ackerstaff *et al.*, Phys. Lett. **B404**, 383 (1997); **SMC**—D. Adams *et al.*, Phys. Lett. **B396**, 338 (1997). (Courtesy of R. Voss, 1997.)



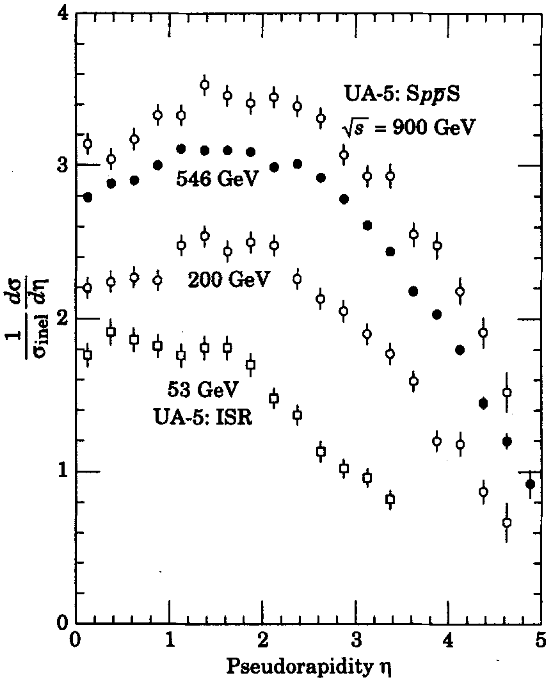
Jet Production in pp and $\bar{p}p$ Interactions

Figure 38.8: Differential cross sections for observation of a single jet of pseudorapidity $\eta = 0$ as a function of the jet transverse momentum. **CDF**—F. Abe *et al.*, Phys. Rev. Lett. **70**, 1376 (1993); **UA1**—G. Arnison *et al.*, Phys. Lett. **B172**, 461 (1986); **UA2**—J. Alitti *et al.*, Phys. Lett. **B257**, 232 (1991); **R807**—T. Akesson *et al.*, Phys. Lett. **B123**, 133 (1983). Next-to-leading order QCD curves are shown for 630 GeV and 1800 GeV. (Courtesy of S. Geer, FNAL, 1995.)



Direct γ Production in $\bar{p}p$ Interactions

Figure 38.9: Differential cross sections for observation of a single photon of pseudorapidity $\eta = 0$ as a function of the photon transverse momentum **R806**—E. Anassontzis *et al.*, Z. Phys. **C13**, 277 (1982); **UA6**—A. Bernasconi *et al.*, Phys. Lett. **B206**, 163 (1988); **UA1**—C. Albajar *et al.*, Phys. Lett. **B209**, 385 (1988); **UA2**—J. Alitti *et al.*, Phys. Lett. **B288**, 386 (1992); **CDF**—F. Abe *et al.*, Phys. Rev. Lett. **73**, 2662 (1994); **DØ**—S. Abachi *et al.*, Phys. Rev. Lett. **77**, 5011 (1996). Next-to-leading order QCD curves are shown for 630 GeV and 1800 GeV. (Courtesy of S. Geer, FNAL, 1995.)



Pseudorapidity Distributions in $\bar{p}p$ Interactions

Figure 38.10: Charge particle pseudorapidity distributions in $p\bar{p}$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 900 GeV. The number per pseudorapidity interval is about 10% higher if the rate is normalized excluding singly diffractive events rather than to the total inelastic rate. Sp$\bar{p}$S data are from G.J. Alner *et al.*, Z. Phys. **C33**, 1 (1986), and ISR data are from K. Alpgård *et al.*, Phys. Lett. **112B**, 193 (1982). CDF nonsingle-diffractive results at $\sqrt{s}$ = 630 and 1800 GeV are given in F. Abe *et al.*, Phys. Rev. **D41**, 2330 (1990). (Courtesy of D.R. Ward, Cambridge Univ., 1991.)

Average Hadron Multiplicities in Hadronic e^+e^- Annihilation Events

Table 38.1: Average hadronic multiplicities per hadronic e^+e^- annihilation event at $\sqrt{s} \approx 10$, 29–35, and 91 GeV. The rates given include decay products from resonances with $c\tau < 10$ cm, and include charge conjugated states. (Updated September 1997 by O. Biebel.)

Particle	$\sqrt{s} \approx 10$ GeV		$\sqrt{s} = 29$–35 GeV		$\sqrt{s} = 91$ GeV	
Pseudoscalar mesons:						
π^+	6.6	$\pm$ 0.2	10.3	$\pm$ 0.4	17.1	$\pm$ 0.4
π^0	3.2	$\pm$ 0.3	5.83	$\pm$ 0.28	9.42	$\pm$ 0.56
K^+	0.90	$\pm$ 0.04	1.48	$\pm$ 0.09	2.39	$\pm$ 0.12
K^0	0.91	$\pm$ 0.05	1.48	$\pm$ 0.07	2.013	$\pm$ 0.033
η	0.20	$\pm$ 0.04	0.61	$\pm$ 0.07	0.97	$\pm$ 0.10
$\eta'(958)$	0.03	$\pm$ 0.01	0.26	$\pm$ 0.10	0.222	$\pm$ 0.040
D^+	0.16	$\pm$ 0.03	0.17	$\pm$ 0.03	0.175	$\pm$ 0.016
D^0	0.37	$\pm$ 0.06	0.45	$\pm$ 0.07	0.454	$\pm$ 0.030
D_s^+	0.13	$\pm$ 0.02	0.45	$\pm 0.20^{(a)}$	0.131	$\pm$ 0.021
B^+, B_d^0		—		—	0.165	$\pm 0.026^{(b)}$
B_s^0		—		—	0.057	$\pm 0.013^{(b)}$
Scalar mesons:						
$f_0(980)$	0.024	$\pm$ 0.006	0.05	$\pm 0.02^{(c)}$	0.14	$\pm 0.06^{(d)}$
Vector mesons:						
$\rho(770)^0$	0.35	$\pm$ 0.04	0.81	$\pm$ 0.08	1.28	$\pm$ 0.14
$\omega(782)$	0.30	$\pm$ 0.08		—	1.10	$\pm$ 0.13
$K^*(892)^+$	0.27	$\pm$ 0.03	0.64	$\pm$ 0.05	0.715	$\pm$ 0.059
$K^*(892)^0$	0.29	$\pm$ 0.03	0.56	$\pm$ 0.06	0.747	$\pm$ 0.028
$\phi(1020)$	0.044	$\pm$ 0.003	0.085	$\pm$ 0.011	0.109	$\pm$ 0.007
$D^*(2010)^+$	0.22	$\pm$ 0.04	0.43	$\pm$ 0.07	0.183	$\pm$ 0.010
$D^*(2007)^0$	0.23	$\pm$ 0.06	0.27	$\pm$ 0.11		—
$B^{*\ (e)}$		—		—	0.288	$\pm$ 0.026
$J/\psi(1S)$		—		—	0.0053	$\pm 0.0004^{(f)}$
$\psi(2S)$		—		—	0.0023	$\pm 0.0004^{(f)}$
$\Upsilon(1S)$		—		—	0.00014	$\pm 0.00007^{(f)}$
Pseudovector mesons:						
$\chi_{c1}(1P)$		—		—	0.0041	$\pm 0.0011^{(f)}$
Tensor mesons:						
$f_2(1270)$	0.09	$\pm$ 0.02	0.14	$\pm$ 0.04	0.31	$\pm$ 0.12
$f_2'(1525)$		—		—	0.020	$\pm$ 0.008
$K_2^*(1430)^+$		—	0.09	$\pm$ 0.03		—
$K_2^*(1430)^0$		—	0.12	$\pm$ 0.06	0.19	$\pm 0.07^{(g)}$
$B^{**\ (h)}$		—		—	0.118	$\pm$ 0.024
Baryons:						
p	0.253	$\pm$ 0.016	0.640	$\pm$ 0.050	0.964	$\pm$ 0.102
Λ	0.080	$\pm$ 0.007	0.205	$\pm$ 0.010	0.372	$\pm$ 0.009
Σ^0	0.023	$\pm$ 0.008		—	0.070	$\pm$ 0.012
Σ^-		—		—	0.071	$\pm$ 0.018
Σ^+		—		—	0.099	$\pm$ 0.015
$\Sigma^\pm$		—		—	0.174	$\pm$ 0.009
Ξ^-	0.0059	$\pm$ 0.0007	0.0176	$\pm$ 0.0027	0.0258	$\pm$ 0.0010
$\Delta(1232)^{++}$	0.040	$\pm$ 0.010		—	0.085	$\pm$ 0.014
$\Sigma(1385)^-$	0.006	$\pm$ 0.002	0.017	$\pm$ 0.004	0.0240	$\pm$ 0.0017
$\Sigma(1385)^+$	0.005	$\pm$ 0.001	0.017	$\pm$ 0.004	0.0239	$\pm$ 0.0015
$\Sigma(1385)^\pm$	0.0106	$\pm$ 0.0020	0.033	$\pm$ 0.008	0.0462	$\pm$ 0.0028
$\Xi(1530)^0$	0.0015	$\pm$ 0.0006		—	0.0055	$\pm$ 0.0005
Ω^-	0.0007	$\pm$ 0.0004	0.014	$\pm$ 0.007	0.0016	$\pm$ 0.0003
Λ_c^+	0.100	$\pm 0.030^{(i)}$	0.110	$\pm$ 0.050	0.078	$\pm$ 0.017
Λ_b^0		—		—	0.031	$\pm$ 0.016
$\Sigma_c^{++}, \Sigma_c^0$	0.014	$\pm$ 0.007		—		—
$\Lambda(1520)$	0.008	$\pm$ 0.002		—		—

All average multiplicites are per hadronic e^+e^- annihilation event.

(a) B($D_s \to \eta\pi$, $\eta'\pi$) has been used (RPP 1994).

(b) The Standard Model B($Z \to b\bar{b}$) = 0.217 was used.

(c) $x_p = p/p_{\text{beam}} > 0.1$ only.

(d) Extrapolation to the unobserved region using the shape predicted by JETSET.

(e) Any charge state (*i.e.*, B_d^*, B_u^*, or B_s^*).

(f) B($Z \to$ hadrons) = 0.699 has been used (RPP 1994).

(g) $x_E = E[K_2^*(1430)^0]/E_{\text{beam}} < 0.3$ only.

(h) Any charge state (*i.e.*, B_d^{**}, B_u^{**}, or B_s^{**}).

(i) The value was taken from the cross section of the $\Lambda_c^+ \to p\pi K$, assuming the branching fraction to be $(3.2 \pm 0.7)\%$ (RPP 1992).

References:

RPP92: Phys. Rev. **D45** (1992) and references therein

RPP94: Phys. Rev. **D50**, 1173 (1994) and references therein

RPP96: Phys. Rev. **D54**, 1 (1996) and references therein

R. Marshall, Rep. Prog. Phys. **52**, 1329 (1989)

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ARGUS: H. Albrecht *et al.*: Phys. Lett. **230B**, 169 (1989); Z. Phys. **C44**, 547 (1989); Z. Phys. **C46**, 15 (1990); Z. Phys. **C54**, 1 (1992); Z. Phys. **C58**, 199 (1993); Z. Phys. **C61**, 1 (1994); Phys. Rep. **276**, 223 (1996)

CELLO: H.J. Behrend *et al.*: Z. Phys. **C46**, 397 (1990); Z. Phys. **C47**, 1 (1990)

CLEO: D. Bortoletto *et al.*, Phys. Rev. **D37**, 1719 (1988)

Crystal Ball: Ch. Bieler *et al.*, Z. Phys. **C49**, 225 (1991)

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L3: M. Acciarri *et al.*: Phys. Lett. **B328**, 223 (1994); Phys. Lett. **B345**, 589 (1995); Phys. Lett. **B371**, 126 (1996); Phys. Lett. **B371**, 137 (1996); Phys. Lett. **B393**, 465 (1997); Phys. Lett. **B404**, 390 (1997); Phys. Lett. **B407**, 351 (1997); Phys. Lett. **B407**, 389 (1997)

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JADE: W. Bartel *et al.*, Z. Phys. **C20**, 187 (1983); and D.D. Pietzl *et al.*, Z. Phys. **C46**, 1 (1990)

OPAL: R. Akers *et al.*: Z. Phys. **C63**, 181 (1994); Z. Phys. **C66**, 555 (1995); Z. Phys. **C67**, 389 (1995); Z. Phys. **C68**, 1 (1995); and G. Alexander *et al.*: Phys. Lett. **B358**, 162 (1995); Z. Phys. **C70**, 197 (1996); Z. Phys. **C72**, 1 (1996); Z. Phys. **C72**, 191 (1996); Z. Phys. **C73**, 569 (1997); Z. Phys. **C73**, 587 (1997); Phys. Lett. **B370**, 185 (1996); and K. Ackerstaff *et al.*: Z. Phys. **C75**, 192 (1997); Z. Phys. C, CERN-PPE/97-093; Z. Phys. C, CERN-PPE/97-094;

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TASSO: H. Aihara *et al.*, Z. Phys. **C27**, 27 (1985)

TPC: H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2378 (1984)

Fragmentation in e^+e^- Annihilation

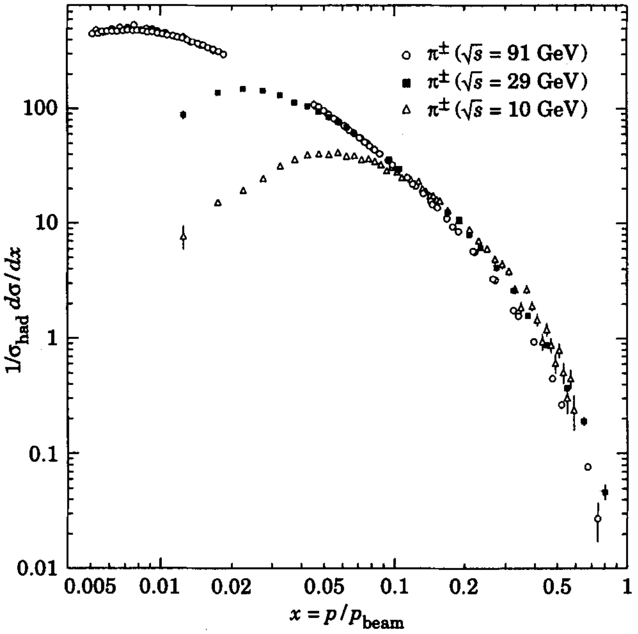


Figure 38.11: Fragmentation into $\pi^\pm$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995); **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

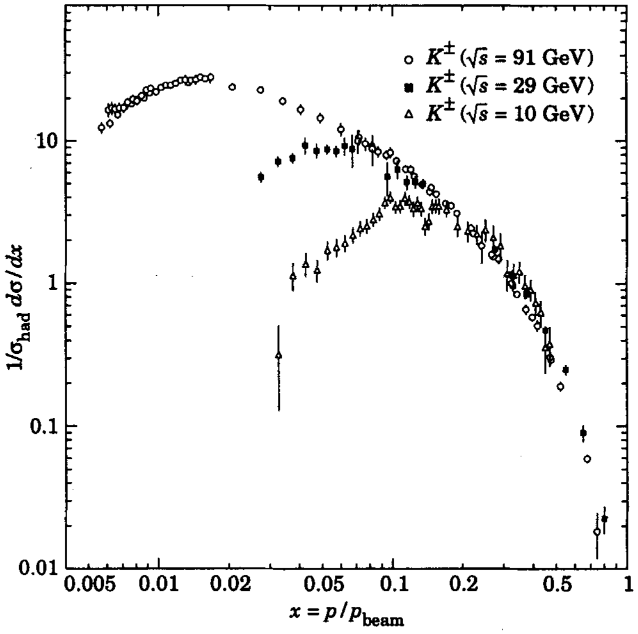


Figure 38.12: Fragmentation into $K^\pm$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995); **DELPHI**—P. Abreu *et al.*, Nucl. Phys. **B444**, 3 (1995); **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

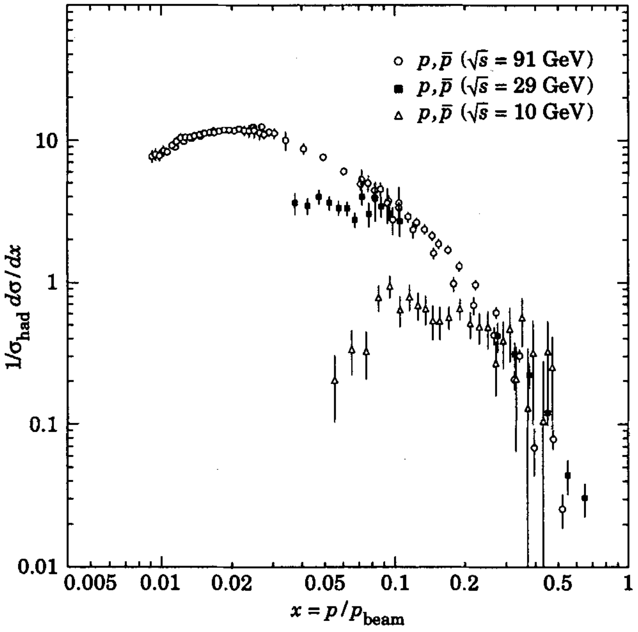


Figure 38.13: Fragmentation into $p\bar{p}$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%. This rate is obtained from the measured $\bar{p}$ rate by scaling with a factor of two: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV: **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV: **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995). **DELPHI**—P. Abreu *et al.*, Nucl. Phys. **B444**, 3 (1995). **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

Annihilation Cross Section Near M_Z

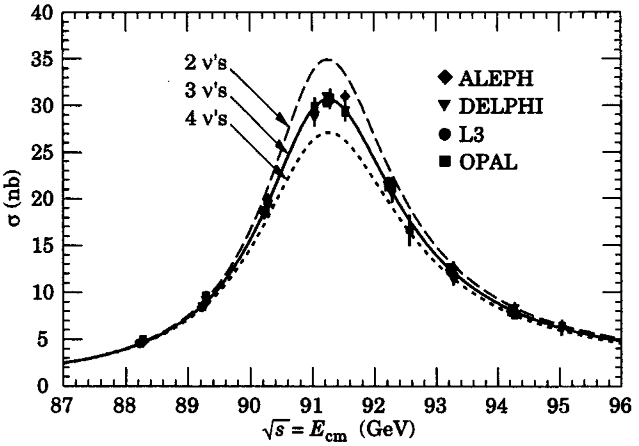


Figure 38.14: Data from the ALEPH, DELPHI, L3, and OPAL Collaborations for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. LEP detectors obtained data at the same energies; some of the points are obscured by overlap. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The asymmetry of the curves is produced by initial-state radiation. References:

ALEPH: D. Decamp *et al.*, Z. Phys. **C53**, 1 (1992).
DEPHI: P. Abreu *et al.*, Nucl. Phys. **B367**, 511 (1992).
L3: B. Adeva *et al.*, Z. Phys. **C51**, 179 (1991).
OPAL: G. Alexander *et al.*, Z. Phys. **C52**, 175 (1991).

Average e^+e^-, pp, and $\bar{p}p$ Multiplicity

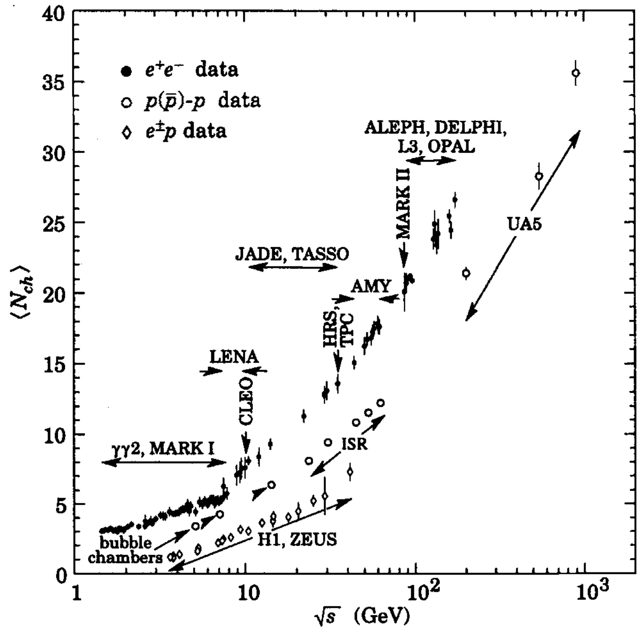


Figure 38.15: Average multiplicity as a function of $\sqrt{s}$ for e^+e^- and $p\bar{p}$ annihilations, and pp and ep collisions. The indicated errors are statistical and systematic errors added in quadrature, except when no systematic errors are given. Files of the data shown in this figure are given in `http://wwwinfo.cern.ch/b/biebel/www/RPP98/`.

e^+e^-: All e^+e^- measurements include contributions from K^0_s and Λ decays with the exception of the L3 measurements. The $\gamma\gamma 2$ and MARK I measurements contain a systematic 5% error. The five points at the Z resonance have been spread horizontally for clarity: **OPAL**: P.D. Acton *et al.*, Z. Phys. **C53**, 539 (1992) and references therein, **OPAL**: R. Akers *et al.*, Z. Phys. **C68**, 203 (1995), **ALEPH**: D. Buskulic *et al.*, Z. Phys. **C69**, 15 (1995), **ALEPH**: D. Buskulic *et al.*, Z. Phys. **C73**, 409 (1997), **DELPHI**: P. Abreu *et al.*, Z. Phys. C, CERN-PPE/97-108, **DELPHI**: P. Abreu *et al.*, Phys. Lett. **B372**, 172 (1996), **L3**: M. Acciarri *et al.*, Phys. Lett. **B371**, 137 (1996), **L3**: M. Acciarri *et al.*, Phys. Lett. **B404**, 390 (1997), **OPAL**: K. Ackerstaff *et al.*, Z. Phys. **C75**, 193 (1997).

$e^{\pm}p$: Multiplicities have been measured in the current fragmentation region of the Breit frame: **H1**: C. Adloff *et al.*, Nucl. Phys. **B**, DESY 97-108, **ZEUS**: M. Derrick *et al.*, Z. Phys. **C67**, 93 (1995).

$p^{(\bar{p})}$: The errors of the $p^{(\bar{p})}$ measurements are the quadratically added statistical and systematic errors, except for the bubble chamber measurements for which only statistical errors are given in the references. The values measured by UA5 exclude single diffractive dissociation: **bubble chamber**: J. Benecke *et al.*, Nucl. Phys. **B76**, 29 (1976), **bubble chamber**: W.M. Morse *et al.*, Phys. Rev. **D15**, 66 (1977), **ISR**: A. Breakstone *et al.*, Phys. Rev. **D30**, 528 (1984), **UA5**: G.J. Alner *et al.*, Phys. Lett. **B**, 476 (1986), **UA5**: R.E. Ansorge *et al.*, Z. Phys. **C43**, 357 (1989).

(Courtesy of O. Biebel, RWTH, Aachen, 1997.)

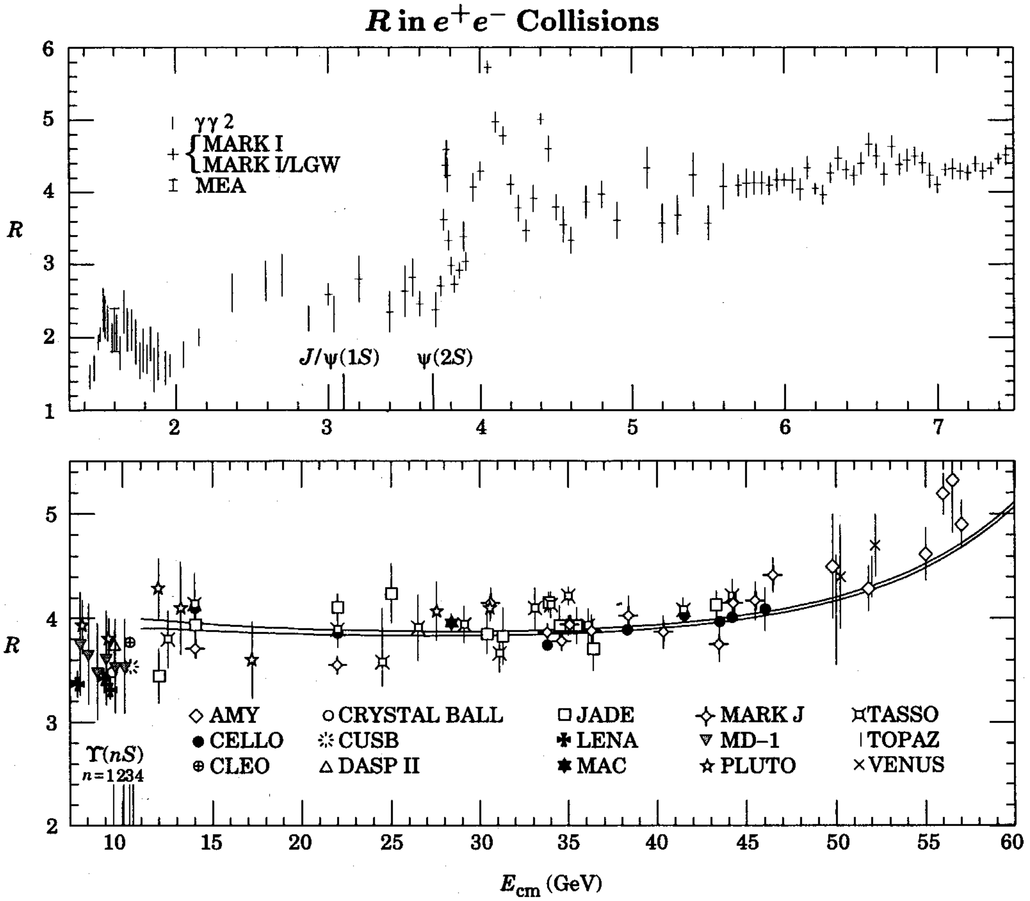


Figure 38.16: Selected measurements of $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, where the annihilation in the numerator proceeds via one photon or via the Z. Measurements in the vicinity of the Z mass are shown in the following figure. The denominator is the calculated QED single-photon process; see the section on Cross-Section Formulae for Specific Processes. Radiative corrections and, where important, corrections for two-photon processes and τ production have been made. Note that the ADONE data ($\gamma\gamma 2$ and MEA) is for ≥ 3 hadrons. The points in the $\psi(3770)$ region are from the MARK I—Lead Glass Wall experiment. To preserve clarity only a representative subset of the available measurements is shown—references to additional data are included below. Also for clarity, some points have been combined or shifted slightly ($< 4\%$) in E_{cm}, and some points with low statistical significance have been omitted. Systematic normalization errors are not included; they range from ~5–20%, depending on experiment. We caution that especially the older experiments tend to have large normalization uncertainties. Note the suppressed zero. The horizontal extent of the plot symbols has no significance. The positions of the $J/\psi(1S)$, $\psi(2S)$, and the four lowest Υ vector-meson resonances are indicated. Two curves are overlaid for $E_{\text{cm}} > 11$ GeV, showing the theoretical prediction for R, including higher order QCD [M. Dine and J. Sapirstein, Phys. Rev. Lett. **43**, 668 (1979)] and electroweak corrections. The Λ values are for 5 flavors in the $\overline{\text{MS}}$ scheme and are $\Lambda^{(5)}_{\overline{\text{MS}}} = 60$ MeV (lower curve) and $\Lambda^{(5)}_{\overline{\text{MS}}} = 250$ MeV (upper curve). (Courtesy of F. Porter, 1992.) References (including several references to data not appearing in the figure and some references to preliminary data):

AMY: T. Mori *et al.*, Phys. Lett. **B218**, 499 (1989);
CELLO: H.-J. Behrend *et al.*, Phys. Lett. **144B**, 297 (1984); and H.-J. Behrend *et al.*, Phys. Lett. **183B**, 400 (1987);
CLEO: R. Giles *et al.*, Phys. Rev. **D29**, 1285 (1984); and D. Besson *et al.*, Phys. Rev. Lett. **54**, 381 (1985);
CUSB: E. Rice *et al.*, Phys. Rev. Lett. **48**, 906 (1982);
CRYSTAL BALL: A. Osterheld *et al.*, SLAC-PUB-4160; and Z. Jakubowski *et al.*, Z. Phys. **C40**, 49 (1988);
DASP: R. Brandelik *et al.*, Phys. Lett. **76B**, 361 (1978);
DASP II: Phys. Lett. **116B**, 383 (1982);
DCI: G. Cosme *et al.*, Nucl. Phys. **B152**, 215 (1979);
DHHM: P. Bock *et al.* (DESY-Hamburg-Heidelberg-MPI München Collab.), Z. Phys. **C6**, 125 (1980);
$\gamma\gamma$2: C. Bacci *et al.*, Phys. Lett. **86B**, 234 (1979);
HRS: D. Bender *et al.*, Phys. Rev. **D31**, 1 (1985);
JADE: W. Bartel *et al.*, Phys. Lett. **129B**, 145 (1983); and W. Bartel *et al.*, Phys. Lett. **160B**, 337 (1985);
LENA: B. Niczyporuk *et al.*, Z. Phys. **C15**, 299 (1982).
MAC: E. Fernandez *et al.*, Phys. Rev. **D31**, 1537 (1985);
MARK J: B. Adeva *et al.*, Phys. Rev. Lett. **50**, 799 (1983); and B. Adeva *et al.*, Phys. Rev. **D34**, 681 (1986);
MARK I: J.L. Siegrist *et al.*, Phys. Rev. **D26**, 969 (1982);
MARK I + Lead Glass Wall: P.A. Rapidis *et al.*, Phys. Rev. Lett. **39**, 526 (1977); and P.A. Rapidis, thesis, SLAC-Report-220 (1979);
MARK II: J. Patrick, Ph.D. thesis, LBL-14585 (1982);
MD-1: A.E. Blinov *et al.*, Z. Phys. **C70**, 31 (1996);
MEA: B. Esposito *et al.*, Lett. Nuovo Cimento **19**, 21 (1977);
PLUTO: A. Bäcker, thesis Gesamthochschule Siegen, DESY F33-77/03 (1977); C. Gerke, thesis, Hamburg Univ. (1979); Ch. Berger *et al.*, Phys. Lett. **81B**, 410 (1979); and W. Lackas, thesis, RWTH Aachen, DESY Pluto-81/11 (1981);
TASSO: R. Brandelik *et al.*, Phys. Lett. **113B**, 499 (1982); and M. Althoff *et al.*, Phys. Lett. **138B**, 441 (1984);
TOPAZ: I. Adachi *et al.*, Phys. Rev. Lett. **60**, 97 (1988); and
VENUS: H. Yoshida *et al.*, Phys. Lett. **198B**, 570 (1987).

Table 38.2: Total hadronic cross section. Regge theory suggests a parameterization of total cross sections as

$$\begin{aligned}\sigma_{AB} &= X_{AB}s^{\epsilon} + Y_{1AB}s^{-\eta_1} + Y_{2AB}s^{-\eta_2}\\ \sigma_{\overline{A}B} &= X_{AB}s^{\epsilon} + Y_{1AB}s^{-\eta_1} - Y_{2AB}s^{-\eta_2}\end{aligned}$$

where X_{AB}, Y_{iAB} are in mb and s is in GeV^2. The exponents ϵ, η_1, and η_2 are independent of the particles $A, \overline{A}$, and B and represent the pomeron, and lower-lying C-even and C-odd exchanges, respectively. Requiring $\eta_1 = \eta_2$ results in much poorer fits. In addition to total cross section, the measured ratio of the real to the imaginary part of the forward scattering amplitude can be included in the fits by assuming that the C-even and C-odd amplitudes have the simple behavior $(-s)^{\alpha} \pm s^{\alpha}$, where $\alpha = 1+\epsilon, 1+\eta_1, 1+\eta_2$. Fits were made to the data for $p^{\pm}p, \pi^{\pm}p, K^{\pm}p, \gamma p$, and $\gamma\gamma$. The exponents $\epsilon = 0.095(2), \eta_1 = 0.34(2)$, and $\eta_2 = 0.55(2)$ thus obtained were then fixed and used as inputs to a fit to a larger data sample that included cross sections on deuterons and neutrons. In the initial fit only data above $\sqrt{s_{\rm min}} = 12$ GeV were used. In the subsequent fit, data above $p_{\rm lab} = 10$ GeV (hadronic collisions) and $\sqrt{s_{\rm min}} = 4$ GeV (γp and $\gamma\gamma$) collisions were used.

Fits to $\overline{p}(p)p$, $\pi^{\pm}p$, $K^{\pm}p$, γp, $\gamma\gamma$			Colliding particles	Fits to groups			χ^2/dof by groups
X	Y_1	Y_2		X	Y_1	Y_2	
18.304(28)	60.12(24)	32.84(33)	$\overline{p}(p)p$	18.256(22)	60.19(21)	33.43(31)	
			$\overline{p}(p)n$	18.256(22)	61.14(58)	29.80(58)	1.17
11.594(22)	27.52(14)	5.53(11)	$\pi^{\pm}p$	11.568(25)	27.55(15)	5.62(13)	1.65
10.353(28)	15.83(20)	12.98(17)	$K^{\pm}p$	10.376(23)	15.57(16)	13.19(17)	
			$K^{\pm}n$	10.376(23)	14.29(37)	7.38(37)	1.26
0.0579(4)	0.1170(26)		γp	0.0577(3)	0.1171(17)		
1.56(18)E-4	0.32(13)E-3		$\gamma\gamma$	1.56(11)E-4	0.32(8)E-3		0.75
$\chi^2/dof = 1.28$ with fixed $\epsilon = 0.095(2)$, $\eta_1 = 0.34(2)$, $\eta_2 = 0.55(2)$ at their central values			$\overline{p}(p)d$	32.357(47)	143.7(7)	85.95(99)	1.57
			$\pi^{\pm}d$	21.015(39)	64.88(51)	1.36(63)	1.91
			$K^{\pm}d$	18.935(40)	35.74(48)	28.80(59)	1.56

The fitted functions are shown in the following figures, along with one-standard-deviation error bands. When the reduced χ^2 is greater than one, a scale factor has been included. Where appropriate, statistical and systematic errors were combined quadratically. Vertical arrows indicate lower limits on the $p_{\rm lab}$ or $E_{\rm cm}$ range used in the fits. The user may decide on the range of applicability of the extrapolated curves. The data were extracted from the PPDS accessible at `http://wwwppds.ihep.su:8001/ppds.html` or `http://pdg.lbl.gov` Computer-readable data files are also available at `http://pdg.lbl.gov`. (Courtesy of V.V. Ezhela, S.B. Lugovsky, and N.P. Tkachenko, COMPAS group, IHEP, Protvino, Russia, April 1998.)

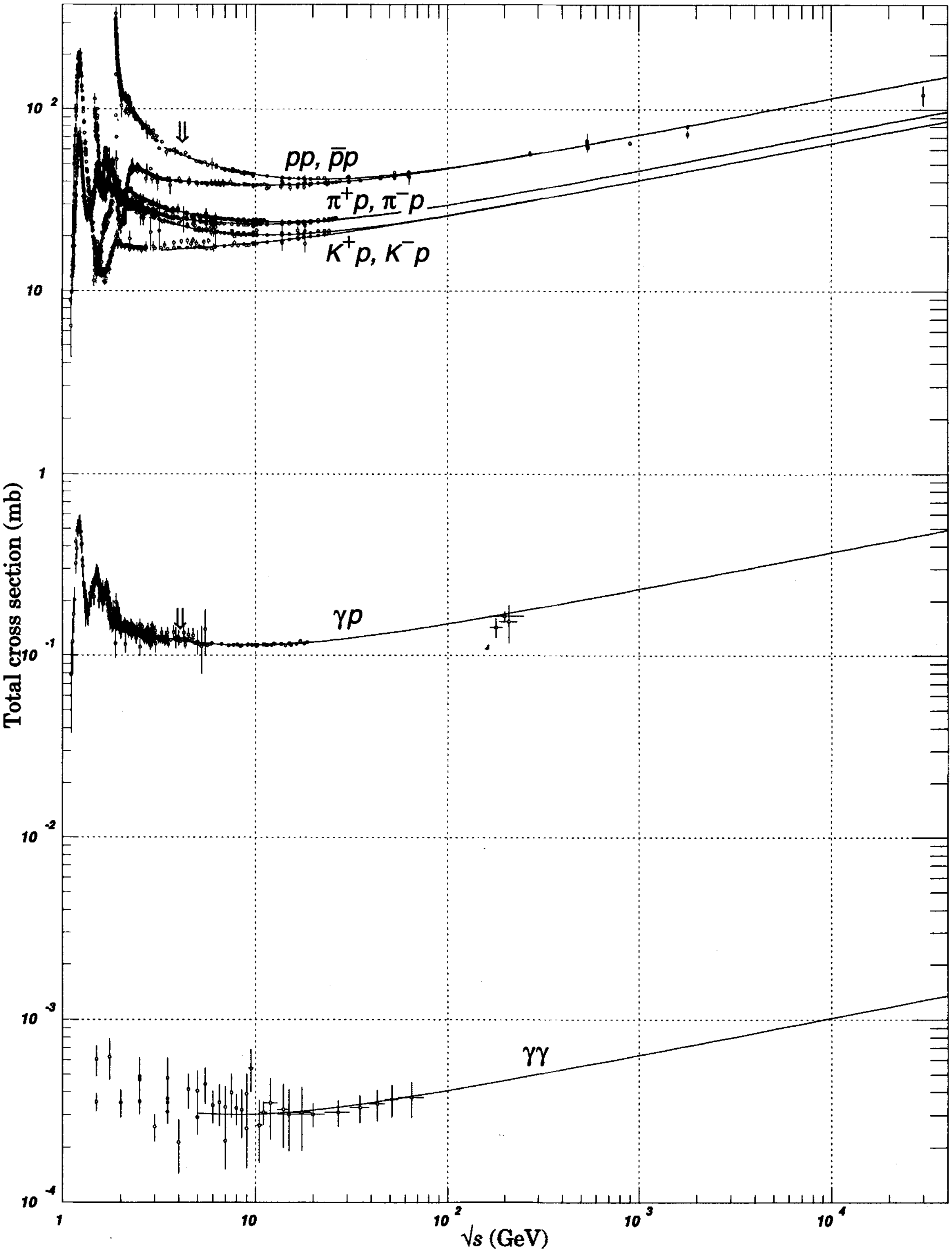


Figure 38.17: Summary of hadronic, γp, and $\gamma\gamma$ total cross sections. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS group, IHEP, Protvino, Russia, April 1998.)

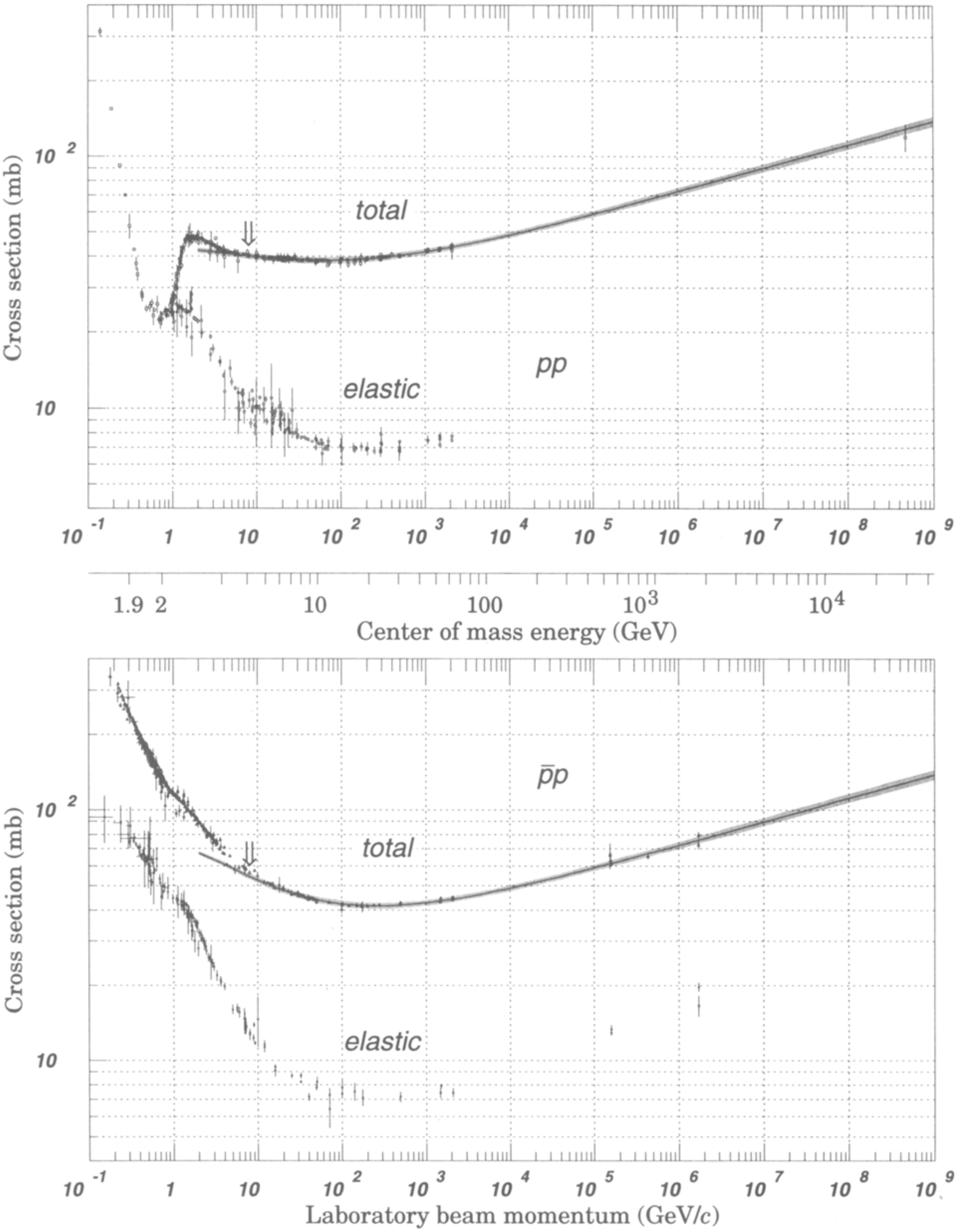


Figure 38.18: Total and elastic cross sections for pp and $\bar{p}p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, April 1998.)

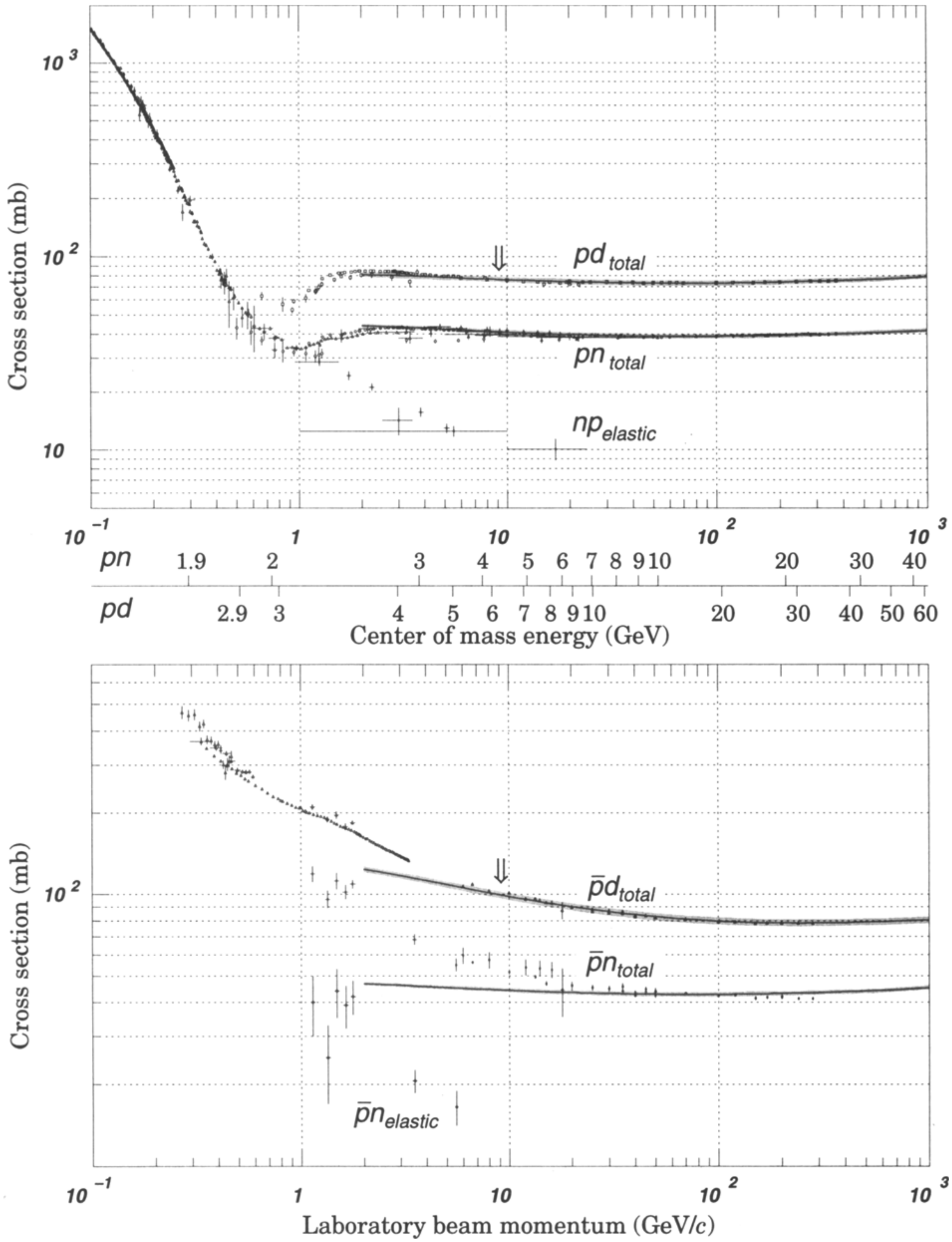


Figure 38.19: Total and elastic cross sections for pd (total only), np, $\bar{p}d$ (total only), and $\bar{p}n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, April 1998.)

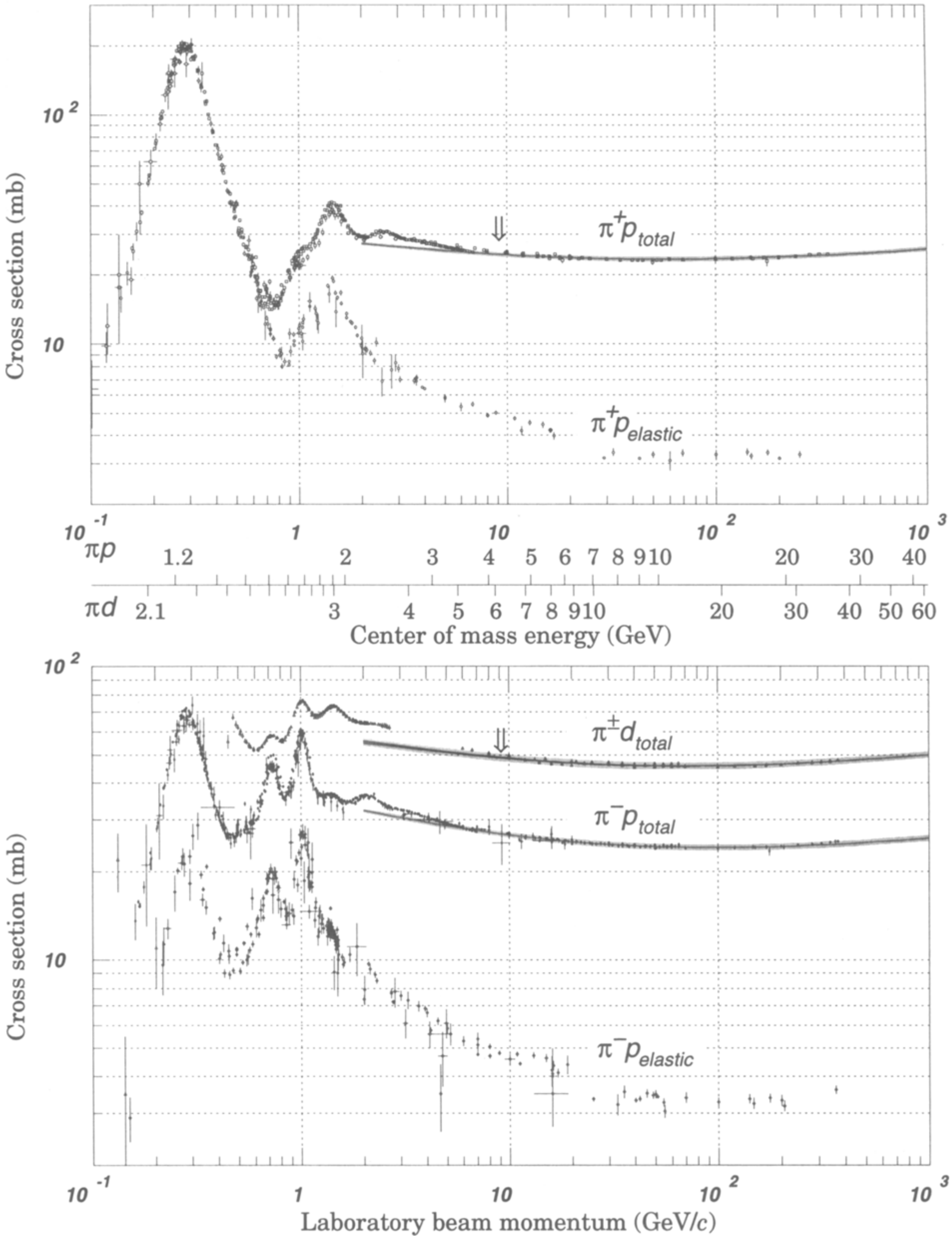


Figure 38.20: Total and elastic cross sections for $\pi^{\pm}p$ and $\pi^{\pm}d$ (total only) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, April 1998.)

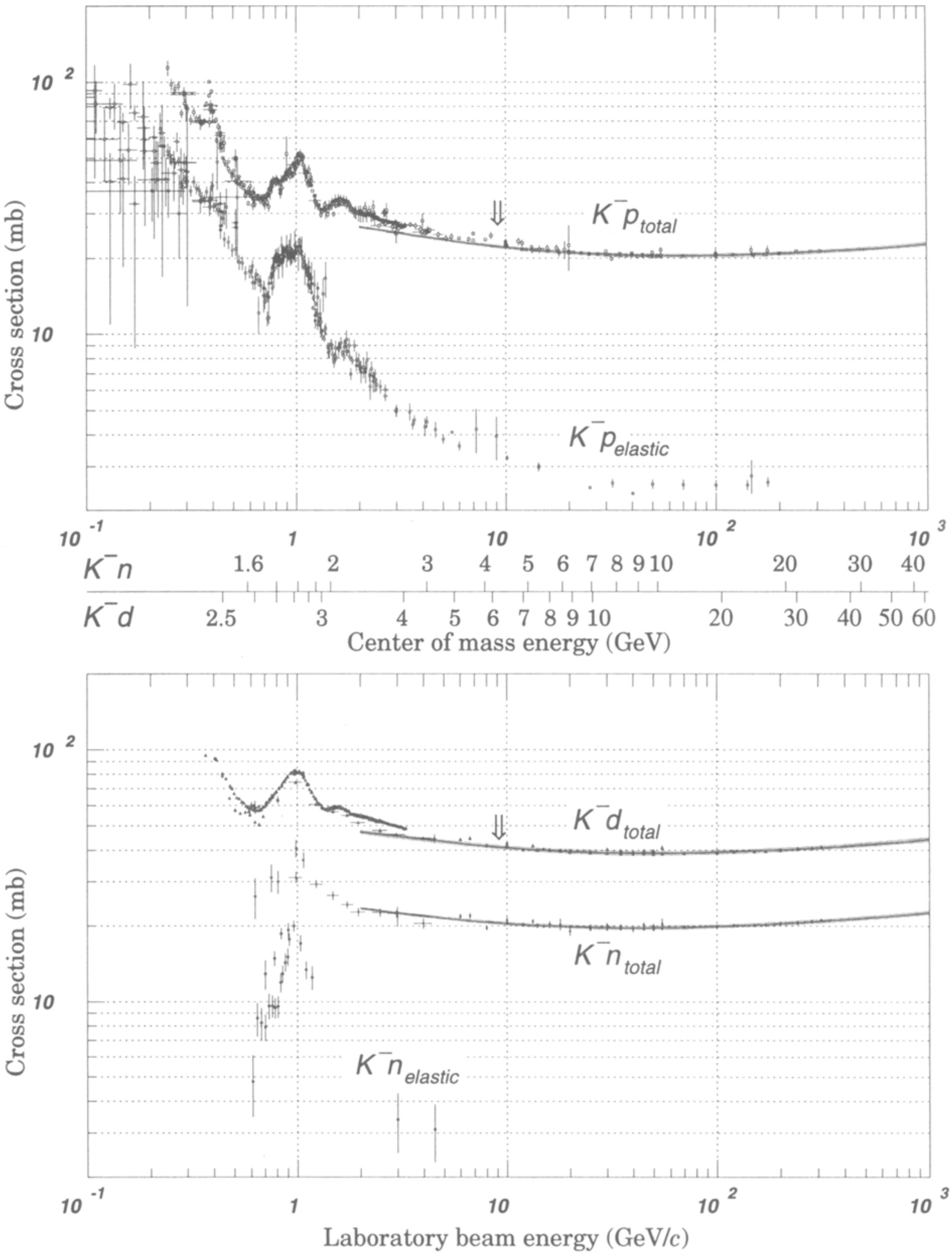


Figure 38.21: Total and elastic cross sections for K^-p and K^-d (total only), and K^-n collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, April 1998.)

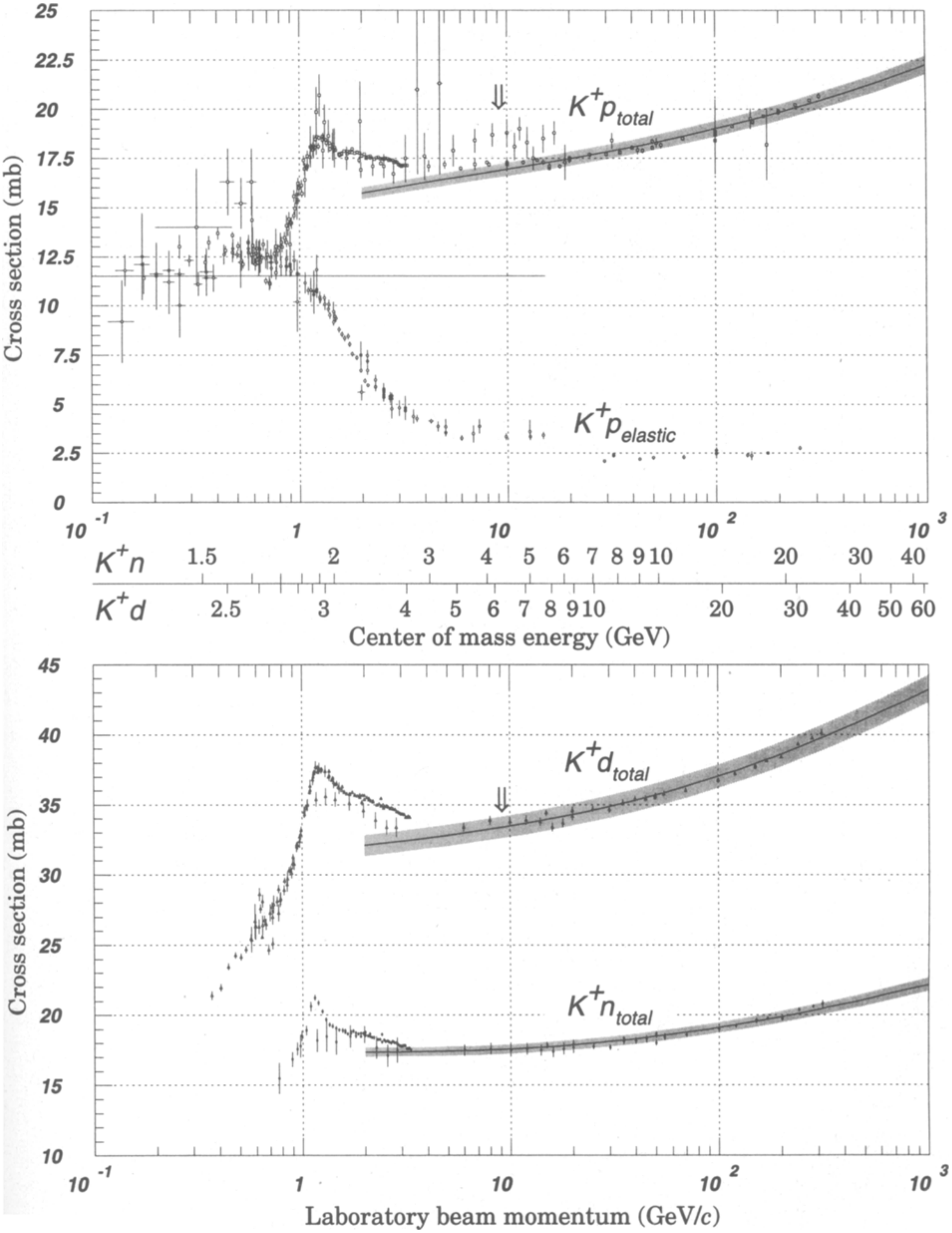


Figure 38.22: Total and elastic cross sections for K^+p and total cross sections for K^+d and K^+n collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, April 1998.)

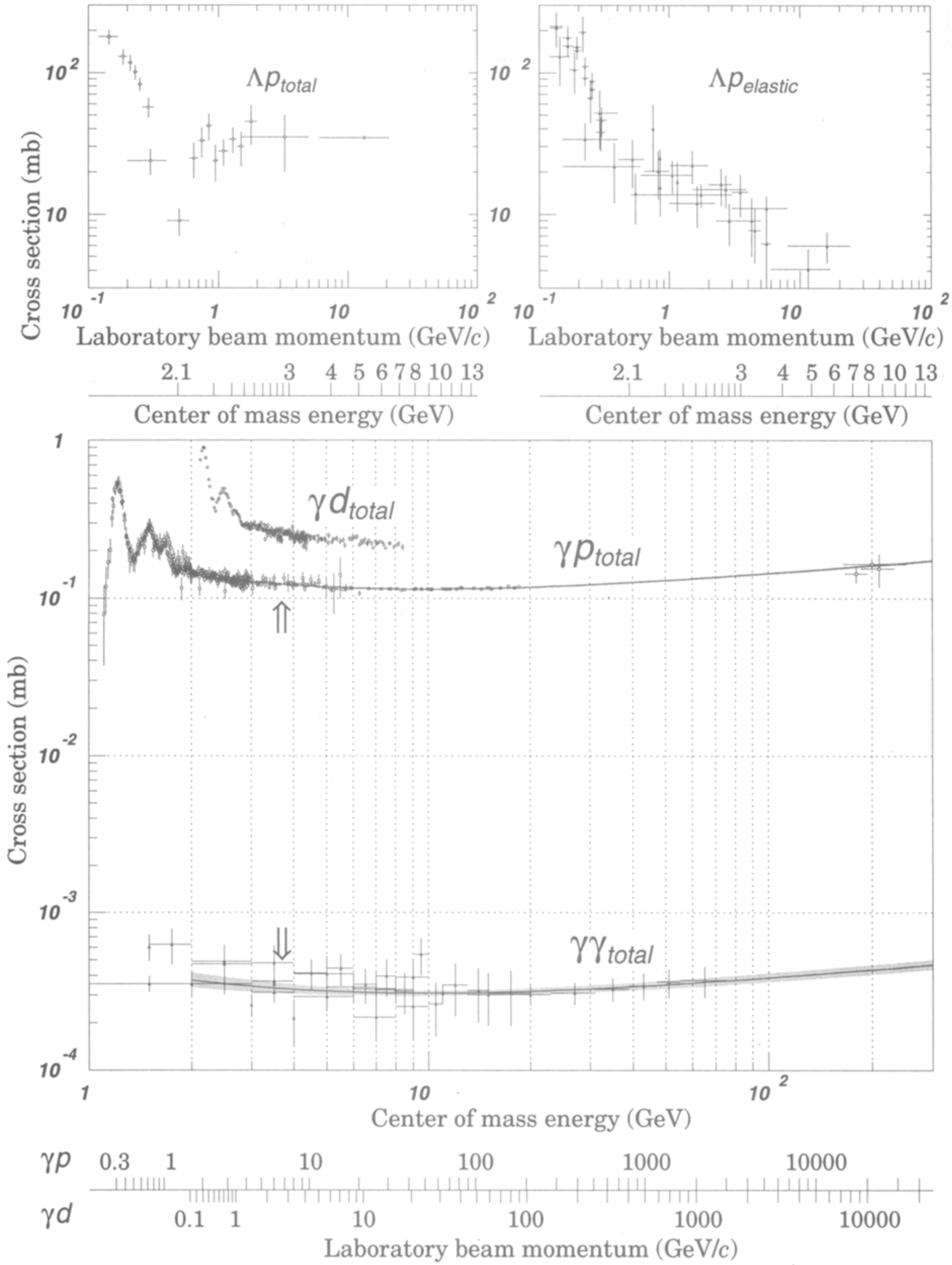


Figure 38.23: Total and elastic cross sections for Λp and total hadronic cross sections for γd, γp, and $\gamma\gamma$ collisions as a function of laboratory beam momentum and the total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS group, IHEP, Protvino, Russia, April 1998.)

INTRODUCTION TO THE PARTICLE LISTINGS

Illustrative Key to the Particle Listings

Name of particle. "Old" name used before 1986 renaming scheme also given if different. See the section "Naming Scheme for Hadrons" for details.

Quantity tabulated below.

Top line gives our best value (and error) of quantity tabulated here, based on weighted average of measurements used. Could also be from fit, best limit, estimate, or other evaluation. See next page for details.

Footnote number linking measurement to text of footnote.

Number of events *above background.*

Measured value used in averages, fits, limits, etc.

Error in measured value (often statistical only; followed by systematic if separately known; the two are combined in quadrature for averaging and fitting.)

Measured value *not used* in averages, fits, limits, etc. See the Introductory Text for explanations.

Arrow points to weighted average.

Shaded pattern extends $\pm 1\sigma$ (scaled by "scale factor" S) from weighted average.

Value and error for each experiment.

Partial decay mode (labeled by Γ_i).

Branching ratio.

Our best value (and error) of quantity tabulated, as determined from constrained fit (using *all significant* measured branching ratios for this particle).

Weighted average of measurements of this ratio only.

Footnote (referring to LYNCH 81).

Confidence level for measured upper limit.

References, ordered inversely by year, then author.

"Document id" used on data entries above.

Journal, report, preprint, etc. (See abbreviations on next page.)

$a_0(1200)$

$I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

Evidence not compelling, may be a kinematic effect.

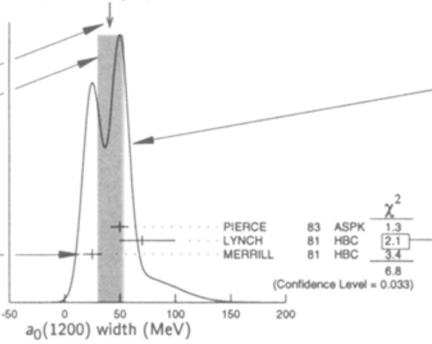
$a_0(1200)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1206± 7 OUR AVERAGE						
1210± 8±9	3000	FENNER	87	MMS	−	3.5 $\pi^- p$
1198±10		PIERCE	83	ASPK	+	2.1 $K^- p$
1216±11±9	1500	[1] MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1192±16	200	LYNCH	81	HBC	±	2.7 $\pi^- p$

[1] Systematic error was added quadratically by us in our 1986 edition.

$a_0(1200)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
41±11 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.						
50± 8		PIERCE	83	ASPK	+	2.1 $K^- p$
70^{+30}_{-20}	200	LYNCH	81	HBC	±	2.7 $\pi^- p$
25± 5±7		MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<60		FENNER	87	MMS	−	3.5 $\pi^- p$



$a_0(1200)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	3π	(65.2±1.3) %	S=1.7
Γ_2	$K\overline{K}$	(34.8±1.3) %	S=1.7
Γ_3	$\eta\pi^\pm$	< 4.9 × 10^{-4}	CL=95%

$a_0(1200)$ BRANCHING RATIOS

$\Gamma(3\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.652±0.013 OUR FIT Error includes scale factor of 1.7.					
0.643±0.010 OUR AVERAGE					
0.64 ±0.01	PIERCE	83	ASPK	+	2.1 $K^- p$
0.74 ±0.06	MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48 ±0.15	[2] LYNCH	81	HBC	±	2.7 $\pi^- p$

[2] Data has questionable background subtraction.

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ **Γ_2/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.348±0.013 OUR FIT Error includes scale factor of 1.7.					
0.35 ±0.05	PIERCE	83	ASPK	+	2.1 $K^- p$

$\Gamma(K\overline{K})/\Gamma(3\pi)$ **Γ_2/Γ_1**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.535±0.030 OUR FIT Error includes scale factor of 1.7.					
0.50 ±0.03	MERRILL	81	HBC	0	3.2 $K^- p$

$\Gamma(\eta(\text{neutral decay})\pi^\pm)/\Gamma_{\text{total}}$ **$0.71\Gamma_3/\Gamma$**

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<3.5	95	PIERCE	83	ASPK	+	2.1 $K^- p$

$a_0(1200)$ REFERENCES

FENNER	87	PRL 55 14	+Watson, Willis, Zorn	(SLAC)
PIERCE	83	PL 123B 230		(FNAL) IJP
LYNCH	81	PR D24 610	+Jones+	(CLEO Collab.)
MERRILL	81	PRL 47 143	+Armstrong, Harper, Rittenberg, Wagman	(SACL, CERN)

Particle quantum numbers (where known).

Indicates particle omitted from Particle Physics Summary Table, implying particle's existence is not confirmed.

General comments on particle.

"Document id" for this result; full reference given below.

Measurement technique. (See abbreviations on next page.)

Scale factor > 1 indicates possibly inconsistent data.

Reaction producing particle, or general comments.

"Change bar" indicates result added or changed since previous edition.

Charge(s) of particle(s) detected.

Ideogram to display possibly inconsistent data. Curve is sum of Gaussians, one for each experiment (area of Gaussian = 1/error; width of Gaussian = ±error). See Introductory Text for discussion.

Contribution of experiment to χ^2 (if no entry present, experiment not used in calculating χ^2 or scale factor because of very large error).

Our best value for branching fraction as determined from data averaging, fitting, evaluating, limit selection, etc. This list is basically a compact summary of results in the Branching Ratio section below.

Branching ratio in terms of partial decay mode(s) Γ_i above.

Partial list of author(s) in addition to first author.

Quantum number determinations in this reference.

Institution(s) of author(s). (See abbreviations on next page.)

Abbreviations Used in the Particle Listings

Indicator of Procedure Used to Obtain Our Result

OUR AVERAGE	From a weighted average of selected data.
OUR FIT	From a constrained or overdetermined multiparameter fit of selected data.
OUR EVALUATION	Not from a direct measurement, but evaluated from measurements of other quantities.
OUR ESTIMATE	Based on the observed range of the data. Not from a formal statistical procedure.
OUR LIMIT	For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

Measurement Techniques (i.e., Detectors and Methods of Analysis)

ACCM	ACCMOR Collaboration
AEMS	Argonne effective mass spectrometer
ALEP	ALEPH - CERN LEP detector
AMY	AMY detector at KEK-TRISTAN
ARG	ARGUS detector at DORIS
ARGD	Fit to semicircular amplitude path on Argand diagram
ASP	Anomalous single-photon detector
ASPK	Automatic spark chambers
ASTE	ASTERIX detector at LEAR
ASTR	Astronomy
B787	BNL experiment 787 detector
B791	BNL experiment 791 detector
B845	BNL experiment 845 detector
BAKS	Baksan underground scintillation telescope
BC	Bubble chamber
BDMP	Beam dump
BEAT	CERN BEATRICE Collab.
BEBC	Big European bubble chamber at CERN
BES	BES Beijing Spectrometer at Beijing Electron-Positron Collider
BIS2	BIS-2 spectrometer at Serpukhov
BKEI	BENKEI spectrometer system at KEK Proton Synchroton
BONA	Bonanza nonmagnetic detector at DORIS
BPWA	Barrelet-zero partial-wave analysis
CALO	Calorimeter
CBAL	Crystal Ball detector at SLAC-SPEAR or DORIS
CBAR	Crystal Barrel detector at CERN-LEAR
CBOX	Crystal Box at LAMPF
CC	Cloud chamber
CCFR	Columbia-Chicago-Fermilab-Rochester detector
CDF	Collider detector at Fermilab
CDHS	CDHS neutrino detector at CERN
CELL	CELLO detector at DESY
CHER	Cherenkov detector
CHM2	CHARM-II neutrino detector (glass) at CERN
CHOZ	Nuclear Power Station near Chooz, France
CHRM	CHARM neutrino detector (marble) at CERN
CIBS	CERN-IHEP boson spectrometer
CLE2	CLEO II detector at CESR
CLEO	Cornell magnetic detector at CESR
CMD	Cryogenic magnetic detector at VEPP-2M, Novosibirsk
CMD2	Cryogenic magnetic detector 2 at VEPP-2M, Novosibirsk
CNTR	Counters
COSM	Cosmology and astrophysics
CPLR	CPLEAR Collaboration
CSB2	Columbia U. - Stony Brook BGO calorimeter inserted in NaI array
CUSB	Columbia U. - Stony Brook segmented NaI detector at CESR
D0	D0 detector at Fermilab Tevatron Collider
DAMA	DAMA, dark matter detector at Gran Sasso National Lab.
DASP	DESY double-arm spectrometer
DBC	Deuterium bubble chamber
DLCO	DELCO detector at SLAC-SPEAR or SLAC-PEP
DLPH	DELPHI detector at LEP
DM1	Magnetic detector no. 1 at Orsay DCI collider
DM2	Magnetic detector no. 2 at Orsay DCI collider
DPWA	Energy-dependent partial-wave analysis
E621	Fermilab E621 detector
E653	Fermilab E653 detector
E665	Fermilab E665 detector
E687	Fermilab E687 detector
E691	Fermilab E691 detector
E705	Fermilab E705 Spectrometer-Calorimeter
E731	Fermilab E731 Spectrometer-Calorimeter
E760	Fermilab E760 detector
E761	Fermilab E761 detector
E771	Fermilab E771 detector
E773	Fermilab E773 Spectrometer-Calorimeter
E789	Fermilab E789 detector
E791	Fermilab E791 detector
E799	Fermilab E799 Spectrometer-Calorimeter
EHS	Four-pi detector at CERN
ELEC	Electronic combination
EMC	European muon collaboration detector at CERN
EMUL	Emulsions
FBC	Freon bubble chamber
FIT	Fit to previously existing data
FMPS	Fermilab Multiparticle Spectrometer
FRAB	ADONE $B\overline{B}$ group detector
FRAG	ADONE $\gamma\gamma$ group detector
FRAM	ADONE MEA group detector
FREJ	FREJUS Collaboration - modular flash chamber detector (calorimeter)
GA24	Hodoscope Cherenkov γ calorimeter (IHEP GAMS-2000) (CERN GAMS-4000)
GALX	GALLEX solar neutrino detector in the Gran Sasso Underground Lab.
GAM2	IHEP hodoscope Cherenkov γ calorimeter GAMS-2000
GAM4	CERN hodoscope Cherenkov γ calorimeter GAMS-4000
GOLI	CERN Goliath spectrometer
H1	H1 detector at DESY/HERA
HBC	Hydrogen bubble chamber
HDBC	Hydrogen and deuterium bubble chambers
HEBC	Helium bubble chamber
HEPT	Helium proportional tubes
HLBC	Heavy-liquid bubble chamber
HOME	Homestake underground scintillation detector
HPW	Harvard-Pennsylvania-Wisconsin detector
HRS	SLAC high-resolution spectrometer
HYBR	Hybrid: bubble chamber + electronics
IMB	Irvine-Michigan-Brookhaven underground Cherenkov detector
IMB3	Irvine-Michigan-Brookhaven underground Cherenkov detector
INDU	Magnetic induction
IPWA	Energy-independent partial-wave analysis
JADE	JADE detector at DESY
KAM2	KAMIOKANDE-II underground Cherenkov detector
KAMI	KAMIOKANDE underground Cherenkov detector
KARM	KARMEN calorimeter at the ISIS neutron spallation source at Rutherford
KOLR	Kolar Gold Field underground detector
KTEV	KTeV Collaboration
L3	L3 detector at LEP
LASS	Large-angle superconducting solenoid spectrometer at SLAC
LATT	Lattice calculations
LEBC	Little European bubble chamber at CERN
LENA	Nonmagnetic lead-glass NaI detector at DORIS
LEPS	Low-Energy Pion Spectrometer at the Paul Scherrer Institute
LSND	Liquid Scintillator Neutrino Detector
MAC	MAC detector at PEP/SLAC
MBR	Molecular beam resonance technique
MCRO	MACRO detector in Gran Sasso
MD1	Magnetic detector at VEEP-4, Novosibirsk
MDRP	Millikan drop measurement
MICA	Underground mica deposits
MIRA	MIRABELLE Liquid-hydrogen bubble chamber
MLEV	Magnetic levitation
MMS	Missing mass spectrometer
MPS	Multiparticle spectrometer at BNL
MPS2	Multiparticle spectrometer upgrade at BNL
MPSF	Multiparticle spectrometer at Fermilab
MPWA	Model-dependent partial-wave analysis
MRK1	SLAC Mark-I detector
MRK2	SLAC Mark-II detector
MRK3	SLAC Mark-III detector
MRKJ	Mark-J detector at DESY
MRS	Magnetic resonance spectrometer
MWPC	Multi-Wire Proportional Chamber
NA14	CERN
NA31	CERN NA31 Spectrometer-Calorimeter
NA32	CERN NA32 Spectrometer
NA48	CERN NA48 Collaboration
ND	NaI detector at VEPP-2M, Novosibirsk
NICE	Serpukhov nonmagnetic precision spectrometer

Abbreviations Used in the Particle Listings *(Cont'd)*

NMR	Nuclear magnetic resonance
NUSX	Mont Blanc NUSEX underground detector
OBLX	OBELIX detector at LEAR
OLYA	Detector at VEPP-2M and VEPP-4, Novosibirsk
OMEG	CERN OMEGA spectrometer
OPAL	OPAL detector at LEP
OSPK	Optical spark chamber
PLAS	Plastic detector
PLUT	DESY PLUTO detector
PWA	Partial-wave analysis
REDE	Resonance depolarization
RVUE	Review of previous data
SAGE	US - Russian Gallium Experiment
SFM	CERN split-field magnet
SHF	SLAC Hybrid Facility Photon Collaboration
SIGM	Serpukhov CERN-IHEP magnetic spectrometer (SIGMA)
SILI	Silicon detector
SLD	SLC Large Detector for e^+e^- colliding beams at SLAC
SOU2	Soudan 2 underground detector
SOUD	Soudan underground detector
SPEC	Spectrometer
SPED	From maximum of speed plot or resonant amplitude
SPRK	Spark chamber
SQID	SQUID device
STRC	Streamer chamber
TASS	DESY TASSO detector
THEO	Theoretical or heavily model-dependent result
TOF	Time-of-flight
TOPZ	TOPAZ detector at KEK-TRISTAN
TPC	TPC detector at PEP/SLAC
TPS	Tagged photon spectrometer at Fermilab
TRAP	Penning trap
UA1	UA1 detector at CERN
UA2	UA2 detector at CERN
UA5	UA5 detector at CERN
VES	Vertex Spectrometer Facility at 70 GeV IHEP accelerator
VNS	VENUS detector at KEK-TRISTAN
WA75	CERN WA75 experiment
WA82	CERN WA82 experiment
WA89	CERN WA89 experiment
WIRE	Wire chamber
XEBC	Xenon bubble chamber
ZEUS	ZEUS detector at DESY/HERA

Conferences

Conferences are generally referred to by the location at which they were held (e.g., HAMBURG, TORONTO, CORNELL, BRIGHTON, etc.).

Journals

AA	Astronomy and Astrophysics
ADVP	Advances in Physics
AFIS	Anales de Fisica
AJP	American Journal of Physics
ANP	Annals of Physics
ANPL	Annals of Physics (Leipzig)
ANYAS	Annals of the New York Academy of Sciences
AP	Atomic Physics
APAH	Acta Physica Academiae Scientiarum Hungaricae
APJ	Astrophysical Journal
APJS	Astrophysical Journal Suppl.
APP	Acta Physica Polonica
ARNPS	Annual Review of Nuclear and Particle Science
ARNS	Annual Review of Nuclear Science
ASP	Astroparticle Physics
BAPS	Bulletin of the American Physical Society
BASUP	Bulletin of the Academy of Science, USSR (Physics)
CJNP	Chinese Journal of Nuclear Physics
CJP	Canadian Journal of Physics
CNPP	Comments on Nuclear and Particle Physics
CZJP	Czechoslovak Journal of Physics
DANS	Doklady Akademii nauk SSSR
EPJ	European Physical Journal
EPL	Europhysics Letters
FECAY	Fizika Elementarnykh Chastits i Atomnogo Yadra
HADJ	Hadronic Journal
IJMP	International Journal of Modern Physics
JAP	Journal of Applied Physics
JETP	English Translation of Soviet Physics ZETF
JETPL	English Translation of Soviet Physics ZETF Letters
JINR	Joint Inst. for Nuclear Research
JINRRC	JINR Rapid Communications
JPA	Journal of Physics, A
JPB	Journal of Physics, B
JPCRD	Journal of Physical and Chemical Reference Data
JPG	Journal of Physics, G
JPSJ	Journal of the Physical Society of Japan
LNC	Lettere Nuovo Cimento
MNRA	Monthly Notices of the Royal Astronomical Society
MPL	Modern Physics Letters
NAT	Nature
NC	Nuovo Cimento
NIM	Nuclear Instruments and Methods
NP	Nuclear Physics
NPBPS	Nuclear Physics B Proceedings Supplement
PAN	Physics of Atomic Nuclei (formerly SJNP)
PD	Physics Doklady (Magazine)
PDAT	Physik Daten
PL	Physics Letters
PN	Particles and Nuclei
PPN	Physics of Particles and Nuclei (formerly SJPN)
PPNP	Progress in Particles and Nuclear Physics
PPSL	Proc. of the Physical Society of London
PR	Physical Review
PRAM	Pramana
PRL	Physical Review Letters
PRPL	Physics Reports (Physics Letters C)
PRSE	Proc. of the Royal Society of Edinburgh
PRSL	Proc. of the Royal Society of London, Section A
PS	Physica Scripta
PTP	Progress of Theoretical Physics
PTRSL	Phil. Trans. Royal Society of London
RA	Radiochimica Acta
RMP	Reviews of Modern Physics
RNC	La Rivista del Nuovo Cimento
RPP	Reports on Progress in Physics
RRP	Revue Roumaine de Physique
SCI	Science
SJNP	Soviet Journal of Nuclear Physics
SJPN	Soviet Journal of Particles and Nuclei
SPD	Soviet Physics Doklady (Magazine)
SPU	Soviet Physics - Uspekhi
UFN	Usp. Fiz. Nauk – Russian version of SPU
YAF	Yadernaya Fizika
ZETF	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki
ZETFP	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, Pis'ma v Redakts
ZNAT	Zeitschrift fur Naturforschung
ZPHY	Zeitschrift fur Physik

Institutions

AACH	Phys. Inst. der Techn. Hochschule **Aachen** (Historical, use for general Inst. der Techn. Hochschule)	Aachen, Germany
AACH1	I Phys. Inst. der Techn. Hochschule **Aachen**	Aachen, Germany
AACH3	III Phys. Inst. der Techn. Hochschule **Aachen**	Aachen, Germany
AACHT	Institut für Theoretische Physik	**Aachen**, Germany
AARH	Univ. of **Aarhus**	Aarhus C, Denmark
ABO	**Åbo** Akademi University	Åbo (Turku), Finland
ADEL	**Adelphi** Univ.	Garden City, NY, USA
ADLD	The Univ. of **Adelaide**	Adelaide, SA, Australia
AERE	Atomic Energy Research Estab.	Didcot, United Kingdom
AFRR	**Armed Forces** Radiobiology Res. Inst.	Bethesda, MD, USA
AHMED	Physical Research Lab.	**Ahmedabad**, Gujarat, India
AICH	**Aichi** Univ. of Education	Aichi, Japan
AKIT	**Akita** Univ.	Akita, Japan
ALAH	Univ. of **Alabama (Huntsville)**	Huntsville, AL, USA

ALAT	Univ. of **Alabama (Tuscaloosa)**	Tuscaloosa, AL, USA
ALBA	**SUNY at Albany**	Albany, NY, USA
ALBE	Univ. of **Alberta**	Edmonton, AB, Canada
AMES	**Ames Lab.**	Ames, IA, USA
AMHT	**Amherst** College	Amherst, MA, USA
AMST	Univ. van **Amsterdam**	Amsterdam, The Netherlands
ANIK	NIKHEF	**Amsterdam**, The Netherlands
ANKA	**Middle East** Technical Univ.; Dept. of Physics; Experimental HEP Lab	Ankara, Turkey
ANL	**Argonne** National Lab.; High Energy Physics Division, Bldg. 362; Physics Division, Bldg. 203	Argonne, IL, USA
ANSM	**St. Anselm** Coll.	Manchester, NH, USA
ARCBO	**Arecibo** Observatory	Arecibo, PR, USA
ARIZ	Univ. of **Arizona**	Tucson, AZ, USA
ARZS	**Arizona State** Univ.	Tempe, AZ, USA
ASCI	Russian Academy of Sciences	**Moscow**, Russian Federation
AST	**Inst. of Phys.**	Nankang, Taipei, The Republic of China (Taiwan)
ATEN	NCSR "**Demokritos**"	**Aghia** Paraskevi Attikis, Greece
ATHU	Univ. of **Athens**	Athens, Greece
AUCK	Univ. of **Auckland**	Auckland, New Zealand
BAKU	**Azerbaijan Academy of Sciences**, Inst. of Physics	**Baku**, Azerbaijan
BANGB	**Bangabasi** College	Calcutta, India
BARC	Univ. Autónoma de **Barcelona**	Bellaterra (Barcelona), Spain
BARI	Univ. di **Bari**	Bari, Italy
BART	Univ. of **Delaware**; **Bartol** Research Inst.	Newark, DE, USA
BASL	Inst. für Physik der Univ. **Basel**	Basel, Switzerland
BAYR	Univ. **Bayreuth**	Bayreuth, Germany
BCEN	Centre d'Etudes Nucleaires de **Bordeaux-Gradignan**	Gradignan, France
BEIJ	**Beijing** Univ.	Beijing, The People's Republic of China
BEIJT	**Inst. of Theoretical Physics**	**Beijing**, The People's Republic of China
BELG	Inter-University Inst. for High Energies (ULB-VUB)	**Brussel**, Belgium
BELL	AT & T **Bell** Labs	Murray Hill, NJ, USA
BERG	Univ. of **Bergen**	Bergen, Norway
BERL	**DESY**	**Zeuthen**, Germany
BERN	Univ. of **Berne**	Berne, Switzerland
BGNA	Univ. di **Bologna**, & INFN, Sezione di Bologna; Viale C. Berti Pichat, n. 6/2; Via Irnerio, 46, I-40126 Bologna	Bologna, Italy
BHAB	**Bhabha Atomic** Research Center	Trombay, Bombay, India
BHEP	**Inst. of High Energy Physics**	**Beijing**, The People's Republic of China
BIEL	Univ. **Bielefeld**	Bielefeld, Germany
BING	**SUNY at Binghamton**	Binghamton, NY, USA
BIRK	**Birkbeck** College, Univ. of London	London, United Kingdom
BIRM	Univ. of **Birmingham**	Edgbaston, Birmingham, United Kingdom
BLSU	**Bloomsburg** Univ.	Bloomsburg, PA, USA
BNL	**Brookhaven National Lab.**	Upton, NY, USA
BOCH	**Ruhr** Univ. **Bochum**	Bochum, Germany
BOHR	**Niels Bohr Inst.**	Copenhagen 0, Denmark
BOIS	**Boise** State Univ.	Boise, ID, USA
BOMB	Univ. of **Bombay**	Bombay, India
BONN	**Rheinische Friedr.-Wilhelms-Univ. Bonn**	Bonn, Germany
BORD	Univ. de **Bordeaux** I	Gradignan, France
BOSE	S.N. **Bose** National Centre for Basis Sciences	Calcutta, India
BOSK	"**Rudjer Bošković**" Inst.	Zagreb, Croatia
BOST	**Boston** Univ.	Boston, MA, USA
BRAN	**Brandeis** Univ.	Waltham, MA, USA
BRCO	Univ. of **British Columbia**	Vancouver, BC, Canada
BRIS	Univ. of **Bristol**	Bristol, United Kingdom
BROW	**Brown** Univ.	Providence, RI, USA
BRUN	**Brunel** Univ.	Uxbridge, Middlesex, United Kingdom
BRUX	Univ. Libre de **Bruxelles**; Service de Physique des Particules Elémentaires	Bruxelles, Belgium
BRUXT	Univ. Libre de **Bruxelles**; Physique Théorique	Bruxelles, Belgium
BUCH	Univ. of **Bucharest**	Bucharest-Magurele, Romania
BUDA	KFKI Research Inst. for Particle & Nuclear Physics	**Budapest**, Hungary
BUFF	**SUNY at Buffalo**	Buffalo, NY, USA
BURE	Inst. des Hautes Etudes Scientifiques	**Bures-sur-Yvette**, France
CAEN	Lab. de Physique Corpusculaire, **ISMRA**	**Caen**, France
CAGL	Univ. degli Studi di **Cagliari**	Cagliari, Italy
CAIR	**Cairo** University	Orman, Giza, Cairo, Egypt
CAIW	**Carnegie Inst.** of Washington	Washington, DC, USA
CALC	Univ. of **Calcutta**	Calcutta, India
CAMB	Univ. of **Cambridge**	Cambridge, United Kingdom
CAMP	Univ. de **Campinas**	**Campinas**, SP, Brasil
CANB	**Australian National Univ.**	Canberra, ACT, Australia
CAPE	University of **Capetown**	Rondebosch, Cape, South Africa
CARA	Univ. Central de **Venezuela**	Caracas, Venezuela
CARL	**Carleton** Univ.	Ottawa, ON, Canada
CARLC	**Carleton** College	Northfield, MN, USA
CASE	**Case** Western Reserve Univ.	Cleveland, OH, USA
CAST	**China** Center of Advanced Science and Technology	Beijing, The People's Republic of China
CATA	Univ. di **Catania**	Catania, Italy
CATH	**Catholic** Univ. of America	Washington, DC, USA
CAVE	**Cavendish** Lab.	Cambridge, United Kingdom
CBNM	CBNM	**Geel**, Belgium
CCAC	**Allegheny** College	Meadville, PA, USA
CDEF	**Collège de France**	Paris, France
CEA	Cambridge Electron Accelerator (Historical in *Review*)	**Cambridge, MA**, USA
CEBAF	**JLab—Thomas Jefferson National Accelerator Facility**	**Newport News**, VA, USA
CENG	Centre d'Etudes Nucleaires	**Grenoble**, France
CERN	**CERN**, European Laboratory for Particle Physics	Genève, Switzerland
CFPA	Univ. of **California, (Berkeley)**	Berkeley, CA, USA
CHIC	Univ. of **Chicago**	Chicago, IL, USA
CIAE	**China Institute of Atomic Energy**	Beijing, The People's Republic of China
CINC	Univ. of **Cincinnati**	Cincinnati, OH, USA
CINV	CINVESTAV-IPN, Centro de Investigacion y de Estudios Avanzados del IPN	**México**, DF, Mexico
CIT	**California Inst. of Tech.**	Pasadena, CA, USA
CLER	Univ. de **Clermont-Ferrand**	Aubière, France
CLEV	**Cleveland** State Univ.	Cleveland, OH, USA
CMNS	**Comenius** Univ.	**Bratislava**, Slovakia
CMU	**Carnegie Mellon** Univ.	Pittsburgh, PA, USA
CNEA	**Comisión Nacional de Energía Atómica**	Buenos Aires, Argentina
CNRC	Centre for Research in Particle Physics	Ottawa, ON, Canada
COLO	Univ. of **Colorado**	Boulder, CO, USA
COLU	**Columbia** Univ.	New York, NY, USA
CONC	**Concordia** University	Montreal, PQ, Canada
CORN	**Cornell** Univ.	Ithaca, NY, USA
COSU	**Colorado State** Univ.	Fort Collins, CO, USA
CPPM	Centre National de la Recherche Scientifique, Luminy	**Marseille**, France
CRAC	**Kraków** Inst. of Nuclear Physics	Kraków, Poland
CRNL	**Chalk River** Labs.	Chalk River, ON, Canada
CSOK	**Oklahoma** Central State Univ.	Edmond, OK, USA
CST	Univ. of **Science and Technology** of China	**Hefei**, Anhui 230027, The People's Republic of China

Abbreviations Used in the Particle Listings *(Cont'd)*

CSULB	**California** State Univ.	Long Beach, CA, USA
CUNY	**City College of New York**	New York, NY, USA
CURIN	**Univ. Pierre et Marie Curie** (Paris VI), LPNHE	Paris, France
CURIT	**Univ. Pierre et Marie Curie** (Paris VI), LPTHE	Paris, France
DALH	**Dalhousie** Univ.	Halifax, NS, Canada
DARE	**Daresbury** Lab	Cheshire, United Kingdom
DARM	Tech. Hochschule **Darmstadt**	Darmstadt, Germany
DELA	Univ. of **Delaware**; Dept. of Physics & Astronomy	Newark, DE, USA
DELH	Univ. of **Delhi**	Delhi, India
DESY	**DESY**, Deutsches Elektronen-Synchrotron	Hamburg, Germany
DFAB	Escuela de Ingenieros	**Bilbao**, Spain
DOE	**Department of Energy**	Germantown, MD, USA
DORT	Univ. **Dortmund**	Dortmund, Germany
DUKE	**Duke** Univ.	Durham, NC, USA
DURH	Univ. of **Durham**	Durham City, United Kingdom
DUUC	**University** College	Dublin, Ireland
EDIN	Univ. of **Edinburgh**	Edinburgh, United Kingdom
EFI	**Enrico Fermi Inst.**	**Chicago**, IL, USA
ELMT	**Elmhurst** College	Elmhurst, IL, USA
ENSP	**l'Ecole Normale Supérieure**	**Paris**, France
EOTV	**Eötvös** University	Budapest, Hungary
EPOL	**École Polytechnique**	**Palaiseau**, France
ERLA	Univ. **Erlangen-Nurnberg**	Erlangen, Germany
ETH	**Univ. Zürich**	Zürich, Switzerland
FERR	Univ. di **Ferrara**	Ferrara, Italy
FIRZ	Univ. di **Firenze**	Firenze, Italy
FISK	**Fisk** Univ.	Nashville, TN, USA
FLOR	Univ. of **Florida**	Gainesville, FL, USA
FNAL	**Fermilab**	Batavia, IL, USA
FOM	**FOM**, Stichting voor Fundamenteel Onderzoek der Materie	JP **Utrecht**, The Netherlands
FRAN	Univ. **Frankfurt**	Frankfurt am Main, Germany
FRAS	Lab. Nazionali di **Frascati** dell'INFN	Frascati (Roma), Italy
FREIB	**Albert-Ludwigs** Univ.	**Freiburg**, Germany
FREIE	**Freie Univ. Berlin**	Berlin, Germany
FRIB	Univ. de **Fribourg**	Fribourg, Switzerland
FSU	**Florida State** University	Tallahassee, FL, USA
FSUSC	**Florida State** Univ.	Tallahassee, FL, USA
FUKI	**Fukui** Univ.	Fukui, Japan
FUKU	**Fukushima** Univ.	Fukushima, Japan
GENO	Univ. di **Genova**	Genova, Italy
GEOR	**Georgian Academy of Sciences**	Tbilisi, Republic of Georgia
GESC	**General Electric** Co.	Schenectady, NY, USA
GEVA	Univ. de **Genève**	Genève, Switzerland
GIES	Univ. **Giessen**	Giessen, Germany
GIFU	**Gifu** Univ.	Gifu, Japan
GLAS	Univ. of **Glasgow**	Glasgow, United Kingdom
GMAS	**George Mason** Univ.	Fairfax, VA, USA
GOET	Univ. **Göttingen**	Göttingen, Germany
GRAN	Univ. de **Granada**	Granada, Spain
GRAZ	Univ. **Graz**	Graz, Austria
GRON	Univ. of **Groningen**	Groningen, The Netherlands
GSCO	**Geological Survey of Canada**	Ottawa, ON, Canada
GSI	**Darmstadt Gesellschaft** fur Schwerionenforschung	Darmstadt, Germany
GUEL	Univ. of **Guelph**	Guelph, ON, Canada
HAHN	**Hahn-Meitner** Inst. Berlin GmbH	Berlin, Germany
HAIF	**Technion** – Israel Inst. of Tech.	Technion, Haifa, Israel
HAMB	Univ. **Hamburg**; I Inst. für Experimentalphysik; II Inst. für Experimentalphysik	Hamburg, Germany
HANN	Univ. **Hannover**	Hannover, Germany
HARC	**Houston Advanced Research Ctr.**	The Woodlands, TX, USA
HARV	**Harvard** Univ.	Cambridge, MA, USA
HAWA	Univ. of **Hawai'i**	Honolulu, HI, USA
HEBR	**Hebrew** Univ.	Jerusalem, Israel
HEID	Univ. **Heidelberg**; (unspecified division) (Historical in *Review*)	Heidelberg, Germany
HEIDH	Univ. **Heidelberg**; Inst. für Hochenergiephysik	Heidelberg, Germany
HEIDP	Univ. **Heidelberg**; Physik Inst.	Heidelberg, Germany
HEIDT	Univ. **Heidelberg**; Inst. für Theoretische Physik	Heidelberg, Germany
HELS	Univ. of **Helsinki**; Dept. of Physics, High Energy Physics Division (SEFO); Dept. of Physics, Theoretical Physics Division (TFO); Helsinki Institute of Physics (HIP)	University of Helsinki, Finland
HIRO	**Hiroshima** Univ.	Higashi-Hiroshima, Japan
HOUS	Univ. of **Houston**	Houston, TX, USA
HPC	**Hewlett-Packard** Corp.	Cupertino, CA, USA
HSCA	**Harvard-Smithsonian** Center for Astrophysics	Cambridge, MA, USA
IAS	**Inst. for Advanced Study**	Princeton, NJ, USA
IASD	**Dublin** Inst. for Advanced Studies	Dublin, Ireland
IBAR	**Ibaraki** Univ.	Ibaraki, Japan
IBM	**IBM** Corp.	Palo Alto, CA, USA
IBMY	**IBM**	Yorktown Heights, NY, USA
IBS	Inst. for **Boson Studies**	Pasadena, CA, USA
ICEPP	Univ. of **Tokyo**; Int. Center for Elementary Particle Physics (ICEPP)	Tokyo, Japan
ICRR	Univ. of **Tokyo**; **Inst. for Cosmic Ray Research**	Tokyo, Japan
ICTP	Abdus Salam International Centre for Theoretical Physics	**Trieste**, Italy
IFIC	**IFIC** (Instituto de Física Corpuscular)	Burjassot, Valencia, Spain
IFRJ	Univ. Federal do **Rio de Janeiro**	Rio de Janeiro, RJ, Brasil
IIT	**Illinois Inst. of Tech.**	Chicago, IL, USA
ILL	Univ. of **Illinois at Urbana-Champaign**	Urbana, IL, USA
ILLC	Univ. of **Illinois at Chicago**	Chicago, IL, USA
ILLG	Inst. **Laue-Langevin**	Grenoble, France
IND	**Indiana** Univ.	Bloomington, IN, USA
INEL	E G and G **Idaho**, Inc.	Idaho Falls, ID, USA
INFN	Ist. Nazionale di Fisica Nuclear (Generic INFN, unknown location)	Various places, Italy
INNS	**Leopold-Franzens** Univ.	**Innsbruck**, Austria
INPK	Inst. of Nuclear Physics	**Kraków**, Poland
INRM	**INR**, Inst. for Nucl. Research	**Moscow**, Russian Federation
INUS	Univ. of **Tokyo**; **Inst. for Nuclear Study**	Tokyo, Japan
IOAN	Univ. of **Ioannina**	Ioannina, Greece
IOFF	A.F. **Ioffe** Phys. Tech. Inst.	St. **Petersburg**, Russian Federation
IOWA	Univ. of **Iowa**	Iowa City, IA, USA
IPN	**IPN**, Inst. de Phys. Nucl.	**Orsay**, France
IPNP	Univ. Pierre et Marie Curie (**Paris** VI)	Paris, France
IRAD	Inst. du Radium (Historical)	**Paris**, France
ISNG	Inst. des Sciences Nucleaires **(ISN)**	**Grenoble**, France
ISU	**Iowa State** Univ., Dept. of Physics & Astronomy; Alpha HEP Group; Ames High Energy Physics	Ames, IA, USA
ITEP	**ITEP**, Inst. of Theor. and Exp. Physics	**Moscow**, Russian Federation
ITHA	**Ithaca** College	Ithaca, NY, USA
IUPU	**Indiana** Univ., **Purdue** Univ. **Indianapolis**	Indianapolis, IN, USA
JADA	**Jadavpur** Univ.	Calcutta, India
JAGL	**Jagiellonian** Univ.	Kraków, Poland
JHU	**Johns Hopkins** Univ.	Baltimore, MD, USA
JINR	**JINR**, Joint Inst. for Nucl. Research	**Dubna**, Russian Federation
JULI	**Julich**, Forschungszentrum	Julich, Germany
JYV	Univ. of **Jyväskylä**	Jyväskylä, Finland

KAGO	Univ. of **Kagoshima**	Kagoshima-shi, Japan
KANS	Univ. of **Kansas**	Lawrence, KS, USA
KARL	Univ. **Karlsruhe**; (unspecified division) (Historical in *Review*)	Karlsruhe, Germany
KARLE	Univ. **Karlsruhe**; Inst. für Experimentelle Kernphysik	Karlsruhe, Germany
KARLK	Forschungszentrum **Karlsruhe**	Karlsruhe, Germany
KARLT	Univ. **Karlsruhe**; Inst. für Theoretische Teilchenphysik	Karlsruhe, Germany
KAZA	**Kazakh** Inst. of High Energy Physics	Alma Ata, Kazakhstan
KEK	**KEK**, National Lab. for High Energy Phys.	Ibaraki-ken, Japan
KENT	Univ. of **Kent**	Canterbury, United Kingdom
KEYN	**Open** Univ.	Milton Keynes, United Kingdom
KFTI	**Kharkov** Inst. of Physics and Tech. (KFTI)	Kharkov, Ukraine
KIAE	The Russian Research Center, **Kurchatov** Inst.	**Moscow**, Russian Federation
KIAM	**Keldysh** Inst. of Applied Math., Acad. Sci., Russia	Moscow, Russian Federation
KIDR	**Vinča Inst. of Nuclear Sciences** (Formerly Boris Kidrič Inst.)	Belgrade, Yugoslavia
KIEV	**Institute for Nuclear Research**	**Kiev**, Ukraine
KINK	**Kinki** Univ.	Osaka, Japan
KNTY	Univ. of **Kentucky**	Lexington, KY, USA
KOBE	**Kobe** Univ.	Kobe, Japan
KOMAB	Univ. of **Tokyo, Komaba**	Tokyo, Japan
KONAN	**Konan** Univ.	Kobe, Japan
KOSI	Inst. of Experimental Physics	**Košice**, Slovakia
KYOT	**Kyoto** Univ.	Kyoto, Japan
KYOTU	**Kyoto** Univ.	Kyoto 606-01, Japan
KYUN	**Kyungpook** National Univ.	Taegu, Republic of Korea
KYUSH	**Kyushu** Univ.	Fukuoka, Japan
LALO	**LAL**, Laboratoire de l'Accélérateur Linéaire	**Orsay**, France
LANC	**Lancaster** Univ.	Lancaster, United Kingdom
LANL	**Los Alamos National Lab.** (LANL)	Los Alamos, NM, USA
LAPP	**LAPP**, Lab. d'Annecy-le-Vieux de Phys. des Particules	**Annecy-le-Vieux**, France
LASL	U.C. **Los Alamos Scientific** Lab. (Old name for LANL)	Los Alamos, NM, USA
LATV	**Latvian** State Univ.	Riga, Latvia
LAUS	Univ. de **Lausanne**	Lausanne, Switzerland
LAVL	Univ. **Laval**	Quebec, PQ, Canada
LBL	**Lawrence Berkeley National Lab.**	Berkeley, CA, USA
LCGT	Univ. di **Torino**	Turin, Italy
LEBD	**Lebedev** Physical Inst.	**Moscow**, Russian Federation
LECE	Univ. di **Lecce**	Lecce, Italy
LEED	Univ. of **Leeds**	Leeds, United Kingdom
LEHI	**Lehigh** Univ.	Bethlehem, PA, USA
LEHM	**Lehman** College of CUNY	Bronx, NY, USA
LEID	Univ. of **Leiden**	Leiden, The Netherlands
LEMO	**Le Moyne** Coll.	Syracuse, NY, USA
LEUV	Katholieke Univ. **Leuven**	Leuven, Belgium
LINZ	Univ. **Linz**	Linz, Austria
LISB	Inst. Nacional de Investigacion Cientifica	**Lisboa** CODEX, Portugal
LISBT	Univ. Técnica de Lisboa, Inst. Superior Técnico	**Lisboa**, Portugal
LIVP	Univ. of **Liverpool**	Liverpool, United Kingdom
LLL	**Lawrence Livermore Lab.** (Old name for LLNL)	Livermore, CA, USA
LLNL	**Lawrence Livermore National Lab.**	Livermore, CA, USA
LOCK	**Lockheed** Palo Alto Res. Lab	Palo Alto, CA, USA
LOIC	**Imperial** College of Science Tech. & Medicine	London, United Kingdom
LOQM	**Univ. of London**, Queen Mary & Westfield College	London, United Kingdom
LOUC	**University College** London	London, United Kingdom

LOUV	Univ. Catholique de **Louvain**	Louvain-la-Neuve, Belgium
LOWC	**Westfield** College (Historical, see LOQM (Queen Mary and Westfield joined))	London, United Kingdom
LRL	U.C. Lawrence Radiation Lab. (Old name for LBL)	**Berkeley**, CA, USA
LSU	**Louisiana** State Univ.	Baton Rouge, LA, USA
LUND	Univ. of **Lund**	Lund, Sweden
LUND	**Fysiska Institutionen**	**Lund**, Sweden
LYON	Institute de Physique Nucléaire de **Lyon** (IPN)	Villeurbanne, France
MADE	Inst. de Estructura de la Materia	**Madrid**, Spain
MADR	**C.I.E.M.A.T**	**Madrid**, Spain
MADU	Univ. Autónoma de **Madrid**	Madrid, Spain
MANI	Univ. of **Manitoba**	Winnipeg, MB, Canada
MANZ	**Johannes-Gutenberg-Univ.**	**Mainz**, Germany
MARB	Univ. **Marburg**	Marburg, Germany
MARS	Centre de Physique des Particules de **Marseille**	Marseille, France
MASA	Univ. of **Massachusetts** Amherst	**Amherst**, MA, USA
MASB	Univ. of **Massachusetts** Boston	**Boston**, MA, USA
MASD	Univ. of **Massachusetts** Dartmouth	N. **Dartmouth**, MA, USA
MCGI	**McGill** Univ.	Montreal, QC, Canada
MCHS	Univ. of **Manchester**	Manchester, United Kingdom
MCMS	**McMaster** Univ.	Hamilton, ON, Canada
MEHTA	**Mehta** Research Inst. of Mathematics & Mathematical Physics	Allahabad, India
MEIS	**Meisei** Univ.	Tokyo, Japan
MELB	Univ. of **Melbourne**	Parkville, Victoria, Australia
MEUD	Observatoire de **Meudon**	Meudon, France
MICH	Univ. of **Michigan**	Ann Arbor, MI, USA
MILA	Univ. di **Milano**	Milano, Italy
MILAI	INFN, Sez. di **Milano**	Milano, Italy
MINN	Univ. of **Minnesota**	Minneapolis, MN, USA
MISS	Univ. of **Mississippi**	University, MS, USA
MISSR	Univ. of **Missouri**	Rolla, MO, USA
MIT	**MIT Massachusetts Inst. of Technology**	Cambridge, MA, USA
MIU	**Maharishi** International Univ.	Fairfield, IA, USA
MIYA	**Miyazaki** Univ.	Miyazaki-shi, Japan
MONP	Univ. de **Montpellier** II	Montpellier, France
MONS	Univ. de **Mons-Hainaut**	**Mons**, Belgium
MONT	Univ. de **Montréal**; Laboratoire René-J.-A.-Lévesque	Montréal, PQ, Canada
MONTC	Univ. de **Montréal**; Centre de recherches mathématiques	Montréal, PQ, Canada
MOSU	**Skobeltsyn** Inst. of Nuclear Physics, Moscow State Univ.	**Moscow**, Russian Federation
MPCM	Max Planck Inst. fur Chemie	**Mainz**, Germany
MPEI	**Moscow Physical Engineering** Inst.	Moscow, Russian Federation
MPIA	**Max-Planck**-Institute für Astrophysik	Garching, Germany
MPIH	**Max-Planck-Inst.** für Kernphysik	**Heidelberg**, Germany
MPIM	**Max-Planck-Inst.** für Physik	**München**, Germany
MSU	**Michigan State** Univ.	East Lansing, MI, USA
MTHO	**Mount Holyoke** College	South Hadley, MA, USA
MULH	Centre Univ. du **Haut-Rhin**	Mulhouse, France
MUNI	**Ludwig-Maximilians-Univ. München**	Garching, Germany
MUNT	Tech. Univ. **München**	Garching, Germany
MURA	**Midwestern** Univ. Research Assoc. (Historical in *Review*)	Stroughton, WI, USA
NAAS	North Americal Aviation Science Center (Historical in *Review*)	Thousand Oaks, CA, USA
NAGO	**Nagoya** Univ.	Nagoya, Japan
NAPL	Univ. di **Napoli**	Napoli, Italy
NASA	**NASA**	Greenbelt, MD, USA

NBS	U.S **National Bureau of Standards** (Old name for NIST)	Gaithersburg, MD, USA
NBSB	**National Inst. Standards Tech.**	Boulder, CO, USA
NCAR	**National Center for Atmospheric Research**	Boulder, CO, USA
NCARO	**North Carolina** State Univ.	**Raleigh**, NC, USA
NDAM	Univ. of **Notre Dame**	Notre Dame, IN, USA
NEAS	**Northeastern** Univ.	Boston, MA, USA
NEUC	Univ. de **Neuchâtel**	Neuchâtel, Switzerland
NICEA	Univ. de **Nice**	Nice, France
NICEO	Observatoire de **Nice**	Nice, France
NIHO	**Nihon** Univ.	Tokyo, Japan
NIIG	**Niigata** Univ.	Niigata, Japan
NIJM	Univ. of **Nijmegen**	Nijmegen, The Netherlands
NIRS	Nat. Inst. Radiological Sciences	**Chiba**, Japan
NIST	**National Institute of Standards & Technology**	Gaithersburg, MD, USA
NIU	**Northern Illinois** Univ.	De Kalb, IL, USA
NMSU	**New Mexico** State Univ.	Las Cruces, NM, USA
NORD	**Nordita**	Copenhagen Ø, Denmark
NOTT	Univ. of **Nottingham**	Nottingham, United Kingdom
NOVM	Inst. of Mathematics	**Novosibirsk**, Russian Federation
NOVO	BINP, **Budker** Inst. of Nuclear Physics	**Novosibirsk**, Russian Federation
NPOL	Polytechnic of **North London**	London, United Kingdom
NRL	**Naval Research** Lab	Washington, DC, USA
NSF	**National Science Foundation**	Arlington, VA, USA
NTHU	**National Tsing Hua** Univ.	Hsinchu, The Republic of China (Taiwan)
NTUA	**National Tech. Univ. of Athens**	Athens, Greece
NWES	**Northwestern** Univ.	Evanston, IL, USA
NYU	**New York** Univ.	New York, NY, USA
OBER	**Oberlin** College	Oberlin, OH, USA
OCH	**Ochanomizu** Univ.	Tokyo, Japan
OHIO	**Ohio** Univ.	Athens, OH, USA
OKAY	**Okayama** Univ.	Okayama, Japan
OKLA	Univ. of **Oklahoma**	Norman, OK, USA
OKSU	**Oklahoma State** Univ.	Stillwater, OK, USA
OREG	Univ. of **Oregon**	Eugene, OR, USA
ORNL	**Oak Ridge** National Laboratory	Oak Ridge, TN, USA
ORSAY	Univ. de **Paris Sud**	**Orsay** CEDEX, France
ORST	**Oregon State** Univ.	Corvallis, OR, USA
OSAK	**Osaka** Univ.	Osaka, Japan
OSKC	**Osaka City** Univ.	Osaka-shi, Japan
OSLO	Univ. of **Oslo**	Oslo, Norway
OSU	**Ohio State** Univ.	Columbus, OH, USA
OTTA	Univ. of **Ottawa**	Ottawa, ON, Canada
OXF	University of **Oxford**	Oxford, United Kingdom
OXFTP	Univ. of **Oxford**	Oxford, United Kingdom
PADO	Univ. degli Studi di **Padova**	Padova, Italy
PARIN	**Univ. Paris VI et Paris VII**, IN^{2}P^3/CNRS	Paris, France
PARIS	Univ. de Paris (Historical)	**Paris**, France
PARIT	**Univ. Paris VI et Paris VII**, LPTHE	Paris, France
PARM	Univ. di **Parma**	Parma, Italy
PAST	Institut **Pasteur**	**Paris**, France
PATR	Univ. of **Patras**	Patras, Greece
PAVI	Univ. di **Pavia**	Pavia, Italy
PENN	Univ. of **Pennsylvania**	Philadelphia, PA, USA
PGIA	Univ. di **Perugia**	Perugia, Italy
PISA	Univ. di **Pisa**	Pisa, Italy
PISAI	**INFN, Sez. di Pisa**	Pisa, Italy
PITT	Univ. of **Pittsburgh**	Pittsburgh, PA, USA
PLAT	**SUNY at Plattsburgh**	Plattsburgh, NY, USA
PLRM	Univ. di **Palermo**	Palermo, Italy
PNL	**Battelle Memorial** Inst.	Richland, WA, USA
PNPI	**Petersburg** Nuclear Physics Inst. of Russian Academy of Sciences	Gatchina, Russian Federation
PPA	Princeton-Penn. Proton Accelerator (Historical in *Review*)	Princeton, NJ, USA
PRAG	Inst. of Physics, **ASCR**	**Prague**, Czech Republic
PRIN	**Princeton** Univ.	Princeton, NJ, USA
PSI	Paul Scherrer Inst.	**Villigen** PSI, Switzerland
PSLL	**Physical Science Lab**	Las Cruces, NM, USA
PSU	**Penn State** Univ.	University Park, PA, USA
PUCB	**Pontifícia Univ. Católica do Rio de Janeiro**	Rio de Janeiro, RJ, Brasil
PUEB	High Energy Physics Group, **FCFM – BUAP**	**Puebla**, Pue, Mexico
PURD	**Purdue** Univ.	West Lafayette, IN, USA
QUKI	**Queen's** Univ.	Kingston, ON, Canada
RAL	**Rutherford Appleton** Lab.	Chilton, Didcot, Oxon., United Kingdom
REGE	Univ. **Regensburg**	Regensburg, Germany
REHO	**Weizmann** Inst. of Science	Rehovot, Israel
RHBL	**Royal Holloway & Bedford** New College	Egham, Surrey, United Kingdom
RHEL	**Rutherford** High Energy Lab (Old name for RAL)	Chilton, Didcot, Oxon., United Kingdom
RICE	**Rice** Univ.	Houston, TX, USA
RIKEN	**Riken** Accelerator Research Facility (RARF)	Saitama, Japan
RIKK	**Rikkyo** Univ.	Tokyo, Japan
RIS	**Rowland** Inst. for Science	Cambridge, MA, USA
RISC	**Rockwell** International	Thousand Oaks, CA, USA
RISL	**Universities Research Reactor**	**Risley**, Warrington, United Kingdom
RISO	**Riso** National Laboratory	Roskilde, Denmark
RL	**Rutherford** High Energy Lab (Old name for RAL)	Chilton, Didcot, Oxon., United Kingdom
RMCS	**Royal Military** Coll. of Science	Swindon, Wilts., United Kingdom
ROCH	Univ. of **Rochester**	Rochester, NY, USA
ROCK	**Rockefeller** Univ.	New York, NY, USA
ROMA	Univ. di **Roma** (Historical)	**Roma**, Italy
ROMA2	Univ. di **Roma**, "Tor Vergata"	Roma, Italy
ROMA3	Univ. di **Roma**	**Roma**, Italy
ROMAI	**INFN, Sez. di Roma**	Roma, Italy
ROSE	**Rose-Hulman** Inst. of Technology	Terre Haute IN, USA
RPI	**Rensselaer Polytechnic** Inst.	Troy, NY, USA
RUTG	**Rutgers** Univ.	Piscataway, NJ, USA
SACL	**CE Saclay**, DAPNIA	Gif-sur-Yvette, France
SACL	**CEA Saclay**	Gif-sur-Yvette, France
SACLD	**CE Saclay**, DAPNIA; Direction	Gif-sur-Yvette, France
SAGA	**Saga** Univ.	Saga-shi, Japan
SANG	**Kyoto Sangyo** Univ.	Kyoto-shi, Japan
SANI	Physics Lab., Ist. Superiore di Sanità	**Roma**, Italy
SASK	Univ. of **Saskatchewan**	Saskatoon, SK, Canada
SASSO	Lab. Naz. del **Gran Sasso** dell'INFN	**Assergi** (L'Aquila), Italy
SAVO	Univ. de **Savoie**	Chambery, France
SBER	**California** State Univ.	**San Bernardino**, CA, USA
SCHAF	W.J. **Schafer** Assoc.	Livermore, DA, USA
SCIT	**Science** Univ. of **Tokyo**	Tokyo, Japan
SCOT	**Scottish** Univ. Research and Reactor Ctr.	Glasgow, United Kingdom
SCUC	Univ. of **South Carolina**	Columbia, SC, USA
SEAT	**Seattle Pacific** Coll.	Seattle, WA, USA
SEIB	Austrian Research Center, **Seibersdorf** LTD.	Seibersdorf, Austria
SEOU	**Korea** Univ.; Dept. of Physics; HEP Group	Seoul, Republic of Korea
SEOUL	**Seoul** National Univ.; Dept. of Physics, Coll. of Natural Sciences; Center for Theoretical Physics	Seoul, Republic of Korea
SERP	**IHEP**, Inst. for High Energy Physics (Also known as Serpukhov)	Protvino, Russian Federation
SETO	**Seton Hall** Univ.	South Orange, NJ, USA
SFLA	Univ. of **South Florida**	Tampa, FL, USA
SFRA	**Simon Fraser University**	Burnaby, BC, Canada

Abbreviations Used in the Particle Listings *(Cont'd)*

SFSU	**California** State Univ.	**San Francisco**, CA, USA
SHAMS	**Ain Shams** University	Kasr-El-Zaafran, Asbasiyah, Cairo, Egypt
SHEF	Univ. of **Sheffield**	Sheffield, United Kingdom
SHMP	Univ. of **Southampton**	Southampton, United Kingdom
SIEG	Univ.-Gesamthochschule-**Siegen**	Siegen, Germany
SILES	Univ. of **Silesia**	Katowice, Poland
SIN	Swiss Inst. of Nuclear Research (Old name for VILL)	**Villigen**, Switzerland
SING	**National Univ.** of Singapore	Kent Ridge, Singapore
SISSA	Scuola Internazionale Superiore di Studi Avanzati	**Trieste**, Italy
SLAC	**Stanford Linear Accelerator Center**	Stanford, CA, USA
SLOV	Inst. of Physics, Slovak Acad. of Sciences	**Bratislava**, Slovakia
SMU	**Southern Methodist** Univ.	Dallas, TX, USA
SNSP	**Scuola Normale Superiore**	**Pisa**, Italy
SOFI	Inst. for Nuclear Research and Nuclear Energy	**Sofia**, Bulgaria
SOFU	Univ. of **Sofia**	Sofia, Bulgaria
SPAUL	Univ. de **São Paulo**	São Paulo, SP, Brasil
SPIFT	Inst. de Física Teórica (**IFT**)	**São Paulo**, SP, Brasil
SSL	Univ. of **California (Berkeley)**; Space Sciences Lab	Berkeley, CA, USA
STAN	**Stanford** Univ.	Stanford, CA, USA
STEV	**Stevens** Inst. of Tech.	Hoboken, NJ, USA
STLO	**St. Louis** Univ.	St. Louis, MO, USA
STOH	**Stockholm** Univ.	Stockholm, Sweden
STON	**SUNY at Stony Brook**	Stony Brook, NY, USA
STRB	**IReS**, Inst. de Recherches Subatomiques	**Strasbourg**, France
STUT	Univ. **Stuttgart**	Stuttgart, Germany
STUTM	Max-Planck-Inst.	**Stuttgart**, Germany
SUGI	**Sugiyama Jogakuen** Univ.	Aichi, Japan
SURR	Univ. of **Surrey**	Guildford, Surrey, United Kingdom
SUSS	Univ. of **Sussex**	Brighton, United Kingdom
SVR	**Savannah** River Labs.	Aiken, SC, USA
SYDN	Univ. of **Sydney**	Sydney, NSW, Australia
SYRA	**Syracuse** Univ.	Syracuse, NY, USA
TAJK	Acad. Sci., Tadzhik SSR	**Dushanbe**, Tadzhikstan
TAMU	**Texas A&M** Univ.	College Station, TX, USA
TATA	**Tata** Inst. of Fundamental Research	Bombay, India
TBIL	**Tbilisi State University**	Tbilisi, Republic of Georgia
TELA	**Tel-Aviv** Univ.	Tel Aviv, Israel
TELE	**Teledyne Brown** Engineering	Huntsville, AL, USA
TEMP	**Temple** Univ.	Philadelphia, PA, USA
TENN	Univ. of **Tennessee**	Knoxville, TN, USA
TEXA	Univ. of **Texas at Austin**	Austin, TX, USA
TGAK	**Tokyo Gakugei** Univ.	Tokyo, Japan
TGU	**Tohoku Gakuin** Univ.	Miyagi, Japan
THES	Aristotle Univ. of **Thessaloniki**	Thessaloniki, Greece
TINT	**Tokyo Inst. of Technology**	Tokyo, Japan
TISA	**Sagamihara** Inst. of Space & Astronautical Sci.	Kanagawa, Japan
TMSK	Inst. Nuclear Physics	**Tomsk**, Russian Federation
TMTC	**Tokyo Metropolitan** Coll. Tech.	Tokyo, Japan
TMU	**Tokyo Metropolitan Univ.**	Tokyo, Japan
TNTO	Univ. of **Toronto**	Toronto, ON, Canada
TOHO	**Toho** Univ.	Chiba, Japan
TOHOK	**Tohoku** Univ.	Sendai, Japan
TOKA	**Tokai** Univ.	Shimizu, Japan
TOKAH	**Tokai** Univ.	Hiratsuka, Japan
TOKMS	Univ. of **Tokyo**; Meson Science Laboratory	Tokyo, Japan
TOKU	Univ. of **Tokushima**	Tokushima-shi, Japan
TOKY	Univ. of **Tokyo**; High-Energy Physics Group	Tokyo, Japan
TOKYC	Univ. of **Tokyo**; Dept. of Chemistry	Tokyo, Japan
TORI	Univ. degli Studi di **Torino**	Torino, Italy
TPTI	Lab. of High Energy Phys.	**Tashkent**, Republic of Uzbekistan
TRIN	Univ. of **Dublin**, Trinity College	**Dublin**, Ireland
TRIU	**TRIUMF**	Vancouver, BC, Canada
TRST	Univ. di **Trieste**	Trieste, Italy
TRSTI	INFN, Sez. di **Trieste**	Trieste, Italy
TRSTT	Univ. di **Trieste**	**Trieste**, Italy
TSUK	Univ. of **Tsukuba**	Ibaraki-ken, Japan
TTAM	**Tamagawa** Univ.	Tokyo, Japan
TUAT	**Tokyo** Univ. of Agriculture Tech.	Tokyo, Japan
TUBIN	Univ. **Tübingen**	Tübingen, Germany
TUFTS	**Tufts** Univ.	Medford, MA, USA
TUW	**Technische Univ. Wien**	Vienna, Austria
UCB	Univ. of **California (Berkeley)**; Dept. of Physics	Berkeley, CA, USA
UCD	Univ. of **California (Davis)**	Davis, CA, USA
UCI	Univ. of **California (Irvine)**	Irvine, CA, USA
UCLA	Univ. of **California (Los Angeles)**	Los Angeles, CA, USA
UCND	**Union Carbide** Corp.	Oak Ridge, TN, USA
UCR	Univ. of **California (Riverside)**	Riverside, CA, USA
UCSB	Univ. of **California (Santa Barbara)**	Santa Barbara, CA, USA
UCSBT	**Inst. for Theoretical Physics**	Santa Barbara, CA, USA
UCSC	Univ. of **California (Santa Cruz)**	Santa Cruz, CA, USA
UCSD	Univ. of **California (San Diego)**	La Jolla, CA, USA
UMD	Univ. of **Maryland**	College Park, MD, USA
UNC	Univ. of **North Carolina**	Greensboro, NC, USA
UNCCH	Univ. of **North Carolina at Chapel Hill**	Chapel Hill, NC, USA
UNCS	**Union** College	Schenectady, NY, USA
UNH	Univ. of **New Hampshire**	Durham, NH, USA
UNM	Univ. of **New Mexico**	Albuquerque, NM, USA
UOEH	Univ. of Occupational and Environmental Health	**Kitakyushu**, Japan
UPNJ	**Upsala** College	East Orange, NJ, USA
UPPS	**Uppsala** Univ.	**Uppsala**, Sweden
UPR	Univ. of **Puerto Rico**	**Rio Piedras**, PR, USA
URI	Univ. of **Rhode Island**	Kingston, RI, USA
USC	Univ. of **Southern California**	Los Angeles, CA, USA
USF	Univ. of **San Francisco**	San Francisco, CA, USA
UTAH	Univ. of **Utah**; Dept. of Physics; High-Energy Astrophysics Inst.	Salt Lake City, UT, USA
UTRE	Univ. of **Utrecht**	Utrecht, The Netherlands
UTRO	**Norwegian Univ. of Science & Technology**	Trondheim, Norway
UZINR	Acad. Sci., **Ukrainian** SSR	**Uzhgorod**, Ukraine
VALE	Univ. de **Valencia**	Burjassot, **Valencia**, Spain
VALP	**Valparaiso** Univ.	Valparaiso, IN, USA
VAND	**Vanderbilt** Univ.	Nashville, TN, USA
VASS	**Vassar** College	Poughkeepsie, NY, USA
VICT	Univ. of **Victoria**	Victoria, BC, Canada
VIEN	Inst. für Hochenergiephysik (HEPHY)	**Vienna**, Austria
VILL	Inst. for Particle Physics of ETH Zürich	**Villigen** PSI, Switzerland
VIRG	Univ. of **Virginia**	Charlottesville, VA, USA
VPI	**Virginia Tech.**	Blacksburg, VA, USA
VRIJ	**Vrije** Univ.	HV **Amsterdam**, The Netherlands
WABRN	Eidgenossisches Amt für Messwesen	**Waber**, Switzerland
WARS	**Warsaw** Univ.	Warsaw, Poland
WASCR	**Waseda** Univ.; Cosmic Ray Division	Tokyo, Japan
WASH	Univ. of **Washington**; Elem. Particle Experiment (EPE); Particle Astrophysics (PA)	Seattle, WA, USA
WASU	**Waseda** Univ.; Dept. of Physics, High Energy Physics Group	Tokyo, Japan

Abbreviations Used in the Particle Listings *(Cont'd)*

WAYN	**Wayne** State Univ.	Detroit, MI, USA
WESL	**Wesleyan** Univ.	Middletown, CT, USA
WIEN	Univ. **Wien**	Vienna, Austria
WILL	Coll. of **William and Mary**	Williamsburg, VA, USA
WINR	Inst. for Nuclear Studies	**Warsaw**, Poland
WISC	Univ. of **Wisconsin**	Madison, WI, USA
WITW	Univ. of the **Witwatersrand**	Wits, South Africa
WMIU	**Western Michigan** Univ.	Kalamazoo, MI, USA
WONT	The Univ. of **Western Ontario**	London, ON, Canada
WOOD	**Woodstock** College (No longer in existence)	Woodstock, MD, USA
WUPP	**Bergische** Univ.	**Wuppertal**, Germany
WURZ	Univ. **Würzburg**	Würzburg, Germany
WUSL	**Washington** Univ.	St. Louis, MO, USA
WYOM	Univ. of **Wyoming**	Laramie, WY, USA
YALE	**Yale** Univ.	New Haven, CT, USA
YARO	**Yaroslavl** State Univ.	Yaroslavl, Russian Federation
YCC	**Yokohama** Coll. of Commerce	Yokohama, Japan
YERE	**Yerevan** Physics Inst.	Yerevan, Armenia
YOKO	**Yokohama National** Univ.	Yokohama-shi, Japan
YORKC	**York** Univ.	Toronto, Canada
ZAGR	**Zagreb** Univ.	Zagreb, Croatia
ZARA	Univ. de **Zaragoza**	Zaragoza, Spain
ZEEM	Univ. van **Amsterdam**	TV Amsterdam, The Netherlands
ZURI	Univ. **Zürich**	Zürich, Switzerland

GAUGE AND HIGGS BOSONS

Notes in the Gauge and Higgs Boson Listings

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

For a review of the photon mass, see BYRNE 77.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{< 2 \times 10^{-16}}$		[1] LAKES	98		Torque on toroid balance
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 9 \times 10^{-16}$	90	[2] FISCHBACH	94		Earth magnetic field
$<(4.73 \pm 0.45) \times 10^{-12}$		[3] CHERNIKOV	92	SQID	Ampere-law null test
$<(9.0 \pm 8.1) \times 10^{-10}$		[4] RYAN	85		Coulomb-law null test
$< 3 \times 10^{-27}$		[5] CHIBISOV	76		Galactic magnetic field
$< 6 \times 10^{-16}$	99.7	DAVIS	75		Jupiter magnetic field
$< 7.3 \times 10^{-16}$		HOLLWEG	74		Alfven waves
$< 6 \times 10^{-17}$		[6] FRANKEN	71		Low freq. res. cir.
$< 1 \times 10^{-14}$		WILLIAMS	71	CNTR	Tests Gauss law
$< 2.3 \times 10^{-15}$		GOLDHABER	68		Satellite data
$< 6 \times 10^{-15}$		[6] PATEL	65		Satellite data
$< 6 \times 10^{-15}$		GINTSBURG	64		Satellite data

[1] LAKES 98 report limits on torque on a toroid Cavendish balance, obtaining a limit on $\mu^2 \boldsymbol{A}$ via the Maxwell-Proca equations, where μ is the proton mass and $\boldsymbol{A}$ is the ambient vector potential in the Lorentz gauge. This is the most conservative limit reported, in which $\boldsymbol{A} \approx (1\,\mu\text{G}) \times (600\,\text{pc})$ is based on the Galactic field.

[2] FISCHBACH 94 report $< 8 \times 10^{-16}$ with unknown CL. We report Baysian CL used elsewhere in these Listings and described in the Statistics section.

[3] CHERNIKOV 92 measures the photon mass at 1.24 K, following a theoretical suggestion that electromagnetic gauge invariance might break down at some low critical temperature. See the erratum for a correction, included here, to the published result.

[4] RYAN 85 measures the photon mass at 1.36 K (see the footnote to CHERNIKOV 92).

[5] CHIBISOV 76 depends in critical way on assumptions such as applicabilty of virial theorem. Some of the arguments given only in unpublished references.

[6] See criticism questioning the validity of these results in KROLL 71 and GOLDHABER 71.

γ CHARGE

VALUE (e)	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{< 5 \times 10^{-30}}$	[7] RAFFELT	94	TOF	Pulsar $f_1 - f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 2 \times 10^{-28}$	[8] COCCONI	92		VLBA radio telescope resolution
$< 2 \times 10^{-32}$	COCCONI	88	TOF	Pulsar $f_1 - f_2$ TOF

[7] RAFFELT 94 notes that COCCONI 88 neglects the fact that the time delay due to dispersion by free electrons in the interstellar medium has the same photon energy dependence as that due to bending of a charged photon in the magnetic field. His limit is based on the assumption that the entire observed dispersion is due to photon charge. It is a factor of 200 less stringent than the COCCONI 88 limit.

[8] See COCCONI 92 for less stringent limits in other frequency ranges. Also see RAFFELT 94 note.

γ REFERENCES

LAKES	98	PRL 80 1826	R. Lakes	(WISC)
FISCHBACH	94	PRL 73 514	+Kloor, Langel+	(PURD, JHU+)
RAFFELT	94	PR D50 7729		(MPIM)
CHERNIKOV	92	PRL 68 3383	+Gerber, Ott, Gerber	(ETH)
Also	92B	PRL 69 2999 (erratum)	Chernikov, Gerber, Ott, Gerber	(ETH)
COCCONI	92	AJP 60 750		(CERN)
COCCONI	88	PL B206 705		(CERN)
RYAN	85	PR D32 802	+Accetta, Austin	(PRIN)
BYRNE	77	Ast.Sp.Sci. 46 115		(LOIC)
CHIBISOV	76	SPU 19 624		(LEBD)
DAVIS	75	PRL 35 1402	+Goldhaber, Nieto	(CIT, STON, LASL)
HOLLWEG	74	PRL 32 961		(NCAR)
FRANKEN	71	PRL 26 115	+Ampulski	(MICH)
GOLDHABER	71	RMP 43 277	+Nieto	(STON, BOHR, UCSB)
KROLL	71	PRL 26 1395		(SLAC)
WILLIAMS	71	PRL 26 721	+Faller, Hill	(WESL)
GOLDHABER	68	PRL 21 567	+Nieto	(STON)
PATEL	65	PL 14 105		(DUKE)
GINTSBURG	64	Sov. Astr. AJ7 536		(ASCI)

g or gluon

$I(J^P) = 0(1^-)$

SU(3) color octet

Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

gluon REFERENCES

YNDURAIN	95	PL B345 524		(MADU)
ABREU	92E	PL B274 498	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ALEXANDER	91H	ZPHY C52 543	+Allison, Allport, Anderson+	(OPAL Collab.)
BEHREND	82D	PL B110 329	+Chen, Field, Guempel, Schroeder+	(CELLO Collab.)
BERGER	80D	PL B97 459	+Genzel, Grigull, Lackas+	(PLUTO Collab.)
BRANDELIK	80C	PL B97 453	+Braunschweig, Gather, Kadansky+	(TASSO Collab.)

graviton

$J = 2$

OMITTED FROM SUMMARY TABLE

graviton MASS

All of the following limits are obtained assuming Yukawa potential in weak field limit. VANDAM 70 argue that a massive field cannot approach general relativity in the zero-mass limit; however, see GOLDHABER 74 and references therein. h_0 is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

VALUE (eV)	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[1] DAMOUR	91	Binary pulsar PSR 1913+16
$< 2 \times 10^{-29}\ h_0^{-1}$	GOLDHABER	74	Rich clusters
$< 7 \times 10^{-28}$	HARE	73	Galaxy
$< 8 \times 10^{4}$	HARE	73	2γ decay

[1] DAMOUR 91 is an analysis of the orbital period change in binary pulsar PSR 1913+16, and confirms the general relativity prediction to 0.8%. "The theoretical importance of the [rate of orbital period decay] measurement has long been recognized as a direct confirmation that the gravitational interaction propagates with velocity c (which is the immediate cause of the appearance of a damping force in the binary pulsar system) and thereby as a test of the existence of gravitational radiation and of its quadrupolar nature." TAYLOR 93 adds that orbital parameter studies now agree with general relativity to 0.5%, and set limits on the level of scalar contribution in the context of a family of tensor [spin 2]-biscalar theories.

graviton REFERENCES

TAYLOR	93	Nature 355 132	+Wolszczan, Damour+	(PRIN, ARCBO, BURE, CARLC) J
DAMOUR	91	APJ 366 501	+Taylor	(BURE, MEUD, PRIN)
GOLDHABER	74	PR D9 119	+Nieto	(LANL, STON)
HARE	73	CJP 51 431		(SASK)
VANDAM	70	NP B22 397	van Dam, Veltman	(UTRE)

W

$J = 1$

NOTE ON THE MASS OF THE W BOSON

Written March 1998 by C. Caso (Univ. of Genova) and A. Gurtu (Tata Inst.)

Till 1995 the production and study of the W boson was the exclusive domain of the $\overline{p}p$ colliders at CERN and FNAL. W production in these hadron colliders is tagged by a high p_T lepton from W decay. Owing to unknown parton–parton effective energy and missing energy in the longitudinal direction, the experiments reconstruct only the transverse mass of the W and derive the W mass from comparing the transverse mass distribution with Monte Carlo predictions as a function of M_W.

In 1996 the energy of LEP was increased in two steps to 161 GeV and 172 GeV, allowing the production of pairs of W bosons. A precise knowledge of the e^+e^- centre of mass energy enables one to reconstruct the W mass even if one of them decays leptonically. At LEP two methods have been used to obtain the W mass. In the first method the measured W-pair production cross sections, $\sigma(e^+e^- \to W^+W^-)$, have been used to determine the W mass using the Standard Model based dependence of this cross section on M_W (see Fig. 1). At 161 GeV, which is just above the W-pair production threshold, this dependence is a much more sensitive function of the W mass than at higher energies.

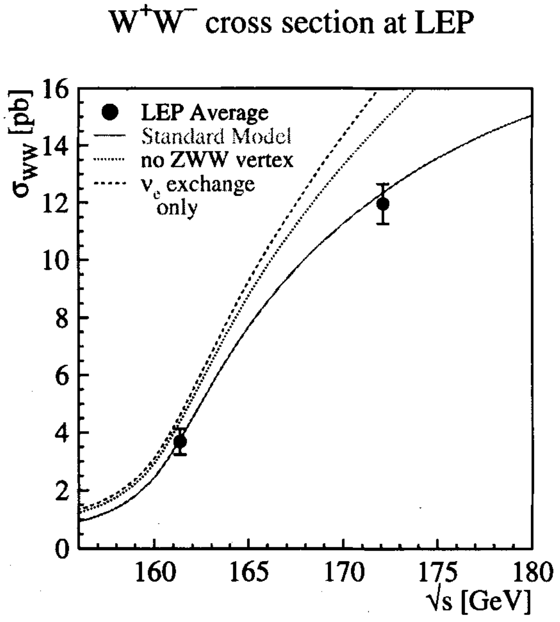


Figure 1: The W-pair cross section as a function of the center-of-mass energy. The data points are the LEP averages. The solid line is the Standard Model prediction. For comparison the figure contains also the cross section if the ZWW coupling did not exist (dotted line), or if only the t-channel ν_e exchange diagram existed (dashed line).

In the second method, which is used at the higher energies, the W mass has been determined by directly reconstructing the W from its decay products.

Each LEP experiment has combined their own mass values properly taking into account the common systematic errors. We have then combined their values into a LEP average leading to: $m_W = 80.49 \pm 0.14$ GeV. The error includes in the systematics a LEP energy uncertainty of ± 30 MeV and, in the case of the reconstruction method for the $q\bar{q}q\bar{q}$ channel, a possible effect of "color reconnection" and "Bose–Einstein correlations" between quarks from different W's. In our combination, the last two effects have been treated as 100% correlated between the experiments.

OUR AVERAGE is obtained by combining this LEP value with other measurements assuming no common systematics.

Combining published and unpublished preliminary Collider and LEP results (as of end of March 1998) yields an average W-boson mass of 80.375 ± 0.064 GeV (80.40 ± 0.09 GeV for p–$\bar{p}$ Colliders and 80.35 ± 0.09 GeV for LEP).

The Standard Model prediction from the electroweak fit, excluding the direct W mass measurements from LEP and Tevatron, gives a W-boson mass of 80.364 ± 0.035 GeV.

W MASS

OUR FIT uses the *W* and *Z* mass, mass difference, and mass ratio measurements.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
80.41 ± 0.10 OUR FIT				
80.41 ± 0.10 OUR AVERAGE				
$80.22 \pm 0.41 \pm 0.07$	72	[1] ABREU 98B	DLPH	$E^{ee}_{\rm cm}$= 172.14 GeV
$80.32 \pm 0.30 \pm 0.094$	96	[2] ACKERSTAFF 98D	OPAL	$E^{ee}_{\rm cm}$= 172.12 GeV
$80.5\ {}^{+1.4}_{-2.2}\ {}^{+0.5}_{-0.6}$	104	[3] ACKERSTAFF 98D	OPAL	$E^{ee}_{\rm cm}$= 172.12 GeV
$80.80 \pm 0.32 \pm 0.114$	95	[4] BARATE 98B	ALEP	$E^{ee}_{\rm cm}$= 172.09 GeV
$80.40 \pm 0.44 \pm 0.095$	29	[5] ABREU 97	DLPH	$E^{ee}_{\rm cm}$= 161.3 GeV
$80.80\ {}^{+0.48}_{-0.42} \pm 0.03$	20	[6] ACCIARRI 97	L3	$E^{ee}_{\rm cm}$= 161.3 GeV
$80.5\ {}^{+1.4}_{-2.4} \pm 0.3$	94	[7] ACCIARRI 97M	L3	$E^{ee}_{\rm cm}$= 172.13 GeV
$80.71\ {}^{+0.34}_{-0.35} \pm 0.09$	101	[8] ACCIARRI 97S	L3	$E^{ee}_{\rm cm}$= 172.13 GeV
$80.14 \pm 0.34 \pm 0.095$	32	[9] BARATE 97	ALEP	$E^{ee}_{\rm cm}$= 161.3 GeV
$81.17\ {}^{+1.15}_{-1.62}$	106	[10] BARATE 97S	ALEP	$E^{ee}_{\rm cm}$= 172.09 GeV
$80.350 \pm 0.140 \pm 0.230$	5982	[11] ABACHI 96E	D0	$E^{p\bar{p}}_{\rm cm}$= 1.8 TeV
$80.40\ {}^{+0.44}_{-0.41}\ {}^{+0.09}_{-0.10}$	23	[12] ACKERSTAFF 96B	OPAL	$E^{ee}_{\rm cm}$= 161.3 GeV
80.410 ± 0.180	8986	[13] ABE 95P	CDF	$E^{p\bar{p}}_{\rm cm}$= 1.8 TeV
79.91 ± 0.39	1722	[14] ABE 90G	CDF	$E^{p\bar{p}}_{\rm cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$84\ {}^{+10}_{-7}$	13	[15] AID 96D	H1	$e^{\pm} p \rightarrow \nu_e(\overline{\nu}_e) + X$ $\sqrt{s} \approx 300$ GeV
$80.84 \pm 0.22 \pm 0.83$	2065	[16] ALITTI 92B	UA2	See *W*/*Z* ratio below
$80.79 \pm 0.31 \pm 0.84$		[17] ALITTI 90B	UA2	$E^{p\bar{p}}_{\rm cm}$= 546,630 GeV
$80.0 \pm 3.3 \pm 2.4$	22	[18] ABE 89I	CDF	$E^{p\bar{p}}_{\rm cm}$= 1.8 TeV
$82.7 \pm 1.0 \pm 2.7$	149	[19] ALBAJAR 89	UA1	$E^{p\bar{p}}_{\rm cm}$= 546,630 GeV
$81.8\ {}^{+6.0}_{-5.3} \pm 2.6$	46	[20] ALBAJAR 89	UA1	$E^{p\bar{p}}_{\rm cm}$= 546,630 GeV
$89 \pm 3 \pm 6$	32	[21] ALBAJAR 89	UA1	$E^{p\bar{p}}_{\rm cm}$= 546,630 GeV
$81. \pm 5.$	6	ARNISON 83	UA1	$E^{ee}_{\rm cm}$= 546 GeV
$80.\ {}^{+10.}_{-6.}$	4	BANNER 83B	UA2	Repl. by ALITTI 90B

[1] ABREU 98B obtain this value from a fit to the reconstructed *W* mass distribution. The *W* width was taken as its Standard Model value at the fitted *W* mass. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ABREU 97 authors find: $M(W) = 80.33 \pm 0.30 \pm 0.06 \pm 0.03$ (LEP) GeV.

[2] ACKERSTAFF 98D obtain this value from a fit to the reconstructed *W* mass distribution. The *W* width was taken as its Standard Model value at the fitted *W* mass. When both *W* mass and width are varied they obtain $M(W) = 80.30 \pm 0.27 \pm 0.095$ GeV. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining both values of ACKERSTAFF 98D with ACKERSTAFF 96B authors find: $M(W) = 80.35 \pm 0.24 \pm 0.07 \pm 0.03$ (LEP) GeV.

[3] ACKERSTAFF 98D derive this value from their measured *W W* production cross section $\sigma_{WW} = 12.3 \pm 1.3 \pm 0.4$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy.

[4] BARATE 98B obtain this value from a fit to the reconstructed *W* mass distribution. The *W* width was taken as its Standard Model value at the fitted *W* mass. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.032 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with the M_W values from cross section measurements at 161 and 172 GeV (BARATE 97 and BARATE 97S) authors find: $M(W) = 80.51 \pm 0.23 \pm 0.08$ GeV.

[5] ABREU 97 derive this value from their measured *W*-*W* production cross section $\sigma_{WW} = 3.67^{+0.97}_{-0.85} \pm 0.19$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. The systematics include an error of ±0.03 GeV arising from the beam energy uncertainty.

[6] ACCIARRI 97 derive this value from their measured *W*-*W* production cross section $\sigma_{WW} = 2.89^{+0.81}_{-0.70} \pm 0.14$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Statistical and systematic errors are added in quadrature and the last error of ±0.03 GeV arises from the beam energy uncertainty. The same result is given by a fit of the production cross sections to the data.

[7] ACCIARRI 97M derive this value from their measured *W W* production cross section $\sigma_{WW} = 12.27^{+1.41}_{-1.32} \pm 0.23$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Combining with ACCIARRI 97 authors find $M(W) = 80.78^{+0.45}_{-0.41} \pm 0.03$ GeV where the last error is due to beam energy uncertainty.

[8] ACCIARRI 97S obtain this value from a fit to the reconstructed *W* mass distribution. The *W* width was taken as its Standard Model value at the fitted *W* mass. When both *W* mass and width are varied they obtain $M(W) = 80.72^{+0.31}_{-0.33} \pm 0.09$ GeV. The systematic error includes ±0.03 GeV due to the beam energy uncertainty and ±0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ACCIARRI 97 and ACCIARRI 97M authors find: $M(W) = 80.75^{+0.26}_{-0.27} \pm 0.03$ (LEP) GeV.

[9] BARATE 97 derive this value from their measured *W*-*W* production cross section $\sigma_{WW} = 4.23 \pm 0.73 \pm 0.19$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. The systematics include an error of ±0.03 GeV arising from the beam energy uncertainty.

[10] BARATE 97S derive this value from their measured $W\,W$ production cross section $\sigma_{W\,W}$ = 11.71 ± 1.23 ± 0.28 pb using the Standard Model dependence of $\sigma_{W\,W}$ on M_W at the given c.m. energy. The errors quoted on the mass are statistical only. Combining with BARATE 97 authors find: $M(W) = 80.20 \pm 0.33 \pm 0.09 \pm 0.03$ (LEP) GeV.

[11] ABACHI 96E fit the transverse mass distribution of 5982 $W \rightarrow e\nu_e$ decays. An error of ±160 MeV due to the uncertainty in the absolute energy scale of the EM calorimeter is included in the total systematics.

[12] ACKERSTAFF 96B derive this value from an analysis of the predicted M_W dependence of their accepted four-fermion cross section, explicitly taking into account interference effects. The systematics include an error of ±0.03 GeV arising from the beam energy uncertainty.

[13] ABE 95P use 3268 $W \rightarrow \mu\nu_\mu$ events to find $M = 80.310 \pm 0.205 \pm 0.130$ GeV and 5718 $W \rightarrow e\nu_e$ events to find $M = 80.490 \pm 0.145 \pm 0.175$ GeV. The result given here combines these while accounting for correlated uncertainties.

[14] ABE 90G result from $W \rightarrow e\nu$ is 79.91 ± 0.35 ± 0.24 ± 0.19(scale) GeV and from $W \rightarrow \mu\nu$ is 79.90 ± 0.53 ± 0.32 ± 0.08(scale) GeV.

[15] AID 96D derive this value as a propagator mass using the Q^2 shape and magnitude of the $e^\pm$ charged-current cross sections. $Q^2 > 5000\,\text{GeV}^2$ events with p_T of the outgoing lepton > 25 GeV/c are used.

[16] ALITTI 92B result has two contributions to the systematic error (±0.83); one (±0.81) cancels in m_W/m_Z and one (±0.17) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP m_Z value, because we perform our own combined fit.

[17] There are two contributions to the systematic error (±0.84): one (±0.81) which cancels in m_W/m_Z and one (±0.21) which is non-cancelling. These were added in quadrature.

[18] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.

[19] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[20] ALBAJAR 89 result is from a total sample of 67 $W \rightarrow \mu\nu$ events.

[21] ALBAJAR 89 result is from $W \rightarrow \tau\nu$ events.

W/Z MASS RATIO

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.8818±0.0011 OUR FIT				
0.8813±0.0036±0.0019	156	[22] ALITTI 92B	UA2	$E^{p\overline{p}}_{\text{cm}} = 630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8831±0.0048±0.0026		[22] ALITTI 90B	UA2	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV

[22] Scale error cancels in this ratio.

$m_Z - m_W$

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.78±0.10 OUR FIT			
10.4 ±1.4 ±0.8	ALBAJAR 89	UA1	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
11.3 ±1.3 ±0.9	ANSARI 87	UA2	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV

$m_{W^+} - m_{W^-}$

Test of *CPT* invariance.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.19±0.58	1722	ABE 90G	CDF	$E^{p\overline{p}}_{\text{cm}} = 1.8$ TeV

W WIDTH

The CDF and DØ widths labelled "extracted value" are obtained by measuring $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \rightarrow e\nu_e)]/(\text{B}(Z \rightarrow ee)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $\text{B}(Z \rightarrow ee)$ measured at LEP. The UA1 and UA2 widths used $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \rightarrow e\nu_e)/\Gamma(Z \rightarrow ee)]\,\Gamma(Z)/\Gamma(W)$ and the measured value of $\Gamma(Z)$. The Standard Model prediction is 2.067 ± 0.021 (ROSNER 94).

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.06 ±0.06 OUR AVERAGE					
$1.30\,^{+0.70}_{-0.55}$ ±0.18		92	[23] ACKERSTAFF 98D	OPAL	$E^{ee}_{\text{cm}} = 172.12$ GeV
$1.74\,^{+0.88}_{-0.78}$ ±0.25		101	[24] ACCIARRI 97S	L3	$E^{ee}_{\text{cm}} = 172.13$ GeV
2.044±0.093		13k	[25] ABACHI 95D	D0	Extracted value
2.11 ±0.28 ±0.16		58	[26] ABE 95C	CDF	Direct meas.
2.064±0.060±0.059			[27] ABE 95W	CDF	Extracted value
$2.10\,^{+0.14}_{-0.13}$ ±0.09		3559	[28] ALITTI 92	UA2	Extracted value
$2.18\,^{+0.26}_{-0.24}$ ±0.04			[29] ALBAJAR 91	UA1	Extracted value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.16 ±0.17			[30] ABE 92I	CDF	Repl. by ABE 95W
2.12 ±0.20			[31] ABE 90	CDF	Repl. by ABE 92I
2.30 ±0.19 ±0.06			[32] ALITTI 90C	UA2	Extracted value
$2.8\,^{+1.4}_{-1.5}$ ±1.3		149	[33] ALBAJAR 89	UA1	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV
<7	90	251	ANSARI 87	UA2	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV
<7	90	119	APPEL 86	UA2	$E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV
<6.5	90	86	[34] ARNISON 86	UA1	Repl. by ALBAJAR 89

[23] ACKERSTAFF 98D obtain this value from a fit to the reconstructed W mass distribution.

[24] ACCIARRI 97S obtain this value from a fit to the reconstructed W mass distribution.

[25] ABACHI 95D measured $R = 10.90 \pm 0.49$ and used the measured value $\text{B}(Z \rightarrow \ell\ell) = (3.367 \pm 0.006)\%$ from LEP.

[26] ABE 95C use the tail of the transverse mass distribution of $W \rightarrow e\nu_e$ decays.

[27] ABE 95W measured $R = 10.90 \pm 0.32 \pm 0.29$. They use $m_W = 80.23 \pm 0.18$ GeV, $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$, $\Gamma(W \rightarrow e\nu) = 225.9 \pm 0.9$ MeV, $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$ GeV.

[28] ALITTI 92 measured $R = 10.4^{+0.7}_{-0.6} \pm 0.3$. The values of $\sigma(Z)$ and $\sigma(W)$ come from $O(\alpha_s^2)$ calculations using $m_W = 80.14 \pm 0.27$ GeV, and $m_Z = 91.175 \pm 0.021$ GeV along with the corresponding value of $\sin^2\theta_W = 0.2274$. They use $\sigma(W)/\sigma(Z) = 3.26 \pm 0.07 \pm 0.05$ and $\Gamma(Z) = 2.487 \pm 0.010$ GeV.

[29] ALBAJAR 91 measured $R = 9.5^{+1.1}_{-1.0}$ (stat. + syst.). $\sigma(W)/\sigma(Z)$ is calculated in QCD at the parton level using $m_W = 80.18 \pm 0.28$ GeV and $m_Z = 91.172 \pm 0.031$ GeV along with $\sin^2\theta_W = 0.2322 \pm 0.0014$. They use $\sigma(W)/\sigma(Z) = 3.23 \pm 0.05$ and $\Gamma(Z) = 2.498 \pm 0.020$ GeV.

[30] ABE 92I report $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ and $106 \pm 10^{+0.2}_{-1}$ $Z \rightarrow \mu^+\mu^-$ events which are combined with 2426 $W \rightarrow e\nu$ events of ABE 91C to derive the ratio $\sigma_W\,\text{B}(W \rightarrow \ell\nu)/\sigma_Z\,\text{B}(Z \rightarrow \ell^+\ell^-) = 10.0 \pm 0.6 \pm 0.4$. Finally the value of $\Gamma(Z)$ measured by LEP 92 is used to extract $\Gamma(W)$.

[31] ABE 90 extract $\Gamma(W) = 2.19 \pm 0.20$ by using the value $\Gamma(Z) = 2.57 \pm 0.07$ GeV. However, in ABE 91C they update their analysis with a new LEP value $\Gamma(Z) = 2.496 \pm 0.016$; the value $\Gamma(W) = 2.12 \pm 0.20$ above reflects this update. They measured $R = 10.2 \pm 0.8 \pm 0.4$, assumed $\sin^2\theta_W = 0.229 \pm 0.007$, and took predicted values $\sigma(W)/\sigma(Z) = 3.23 \pm 0.03$ and $\Gamma(W \rightarrow e\nu)/\Gamma(Z \rightarrow ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E^{p\overline{p}}_{\text{cm}} = 1.8$ TeV.

[32] ALITTI 90C used the same technique as described for ABE 90. They measured $R = 9.38^{+0.82}_{-0.72} \pm 0.25$, obtained $\Gamma(W)/\Gamma(Z) = 0.902 \pm 0.074 \pm 0.024$. Using $\Gamma(Z) = 2.546 \pm 0.032$ GeV, they obtained the $\Gamma(W)$ value quoted above and the limits $\Gamma(W) < 2.56$ (2.64) GeV at the 90% (95%) CL. $E^{p\overline{p}}_{\text{cm}} = 546{,}630$ GeV.

[33] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[34] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

W ANOMALOUS MAGNETIC MOMENT ($\Delta\kappa$)

The full magnetic moment is given by $\mu_W = e(1+\kappa+\lambda)/2m_W$. In the Standard Model, at tree level, $\kappa = 1$ and $\lambda = 0$. Some papers have defined $\Delta\kappa = 1-\kappa$ and assume that $\lambda = 0$. Note that the electric quadrupole moment is given by $-e(\kappa-\lambda)/m^2_W$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m_W$)	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[35] ABE 95G	
	[36] ALITTI 92C	UA2
	[37] SAMUEL 92	THEO
	[38] SAMUEL 91	THEO
	[39] GRIFOLS 88	THEO
	[40] GROTCH 87	THEO
	[41] VANDERBIJ 87	THEO
	[42] GRAU 85	THEO
	[43] SUZUKI 85	THEO
	[44] HERZOG 84	THEO

[35] ABE 95G report $-1.3 < \kappa < 3.2$ for $\lambda=0$ and $-0.7 < \lambda < 0.7$ for $\kappa=1$ in $p\overline{p} \rightarrow e\nu_e\gamma X$ and $\mu\nu_\mu\gamma X$ at $\sqrt{s} = 1.8$ TeV.

[36] ALITTI 92C measure $\kappa = 1^{+2.6}_{-2.2}$ and $\lambda = 0^{+1.7}_{-1.8}$ in $p\overline{p} \rightarrow e\nu\gamma + X$ at $\sqrt{s} = 630$ GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.

[37] SAMUEL 92 use preliminary CDF and UA2 data and find $-2.4 < \kappa < 3.7$ at 96%CL and $-3.1 < \kappa < 4.2$ at 95%CL respectively. They use data for $W\gamma$ production and radiative W decay.

[38] SAMUEL 91 use preliminary CDF data for $p\overline{p} \rightarrow W\gamma X$ to obtain $-11.3 \leq \Delta\kappa \leq 10.9$. Note that their $\kappa = 1-\Delta\kappa$.

[39] GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65\,(M^2_W/\Lambda^2)$.

[40] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \rightarrow \nu\overline{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.

[41] VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33\,(m_W/\Lambda)$. In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.

[42] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa \ln(\Lambda/m_W) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.

[43] SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190 (m_W/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m_W)$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150 (m_W/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.

[44] HERZOG 84 consider the contribution of *W*-boson to muon magnetic moment including anomalous coupling of $WW\gamma$. Obtain a limit $-1 < \Delta\kappa < 3$ for $\Lambda \gtrsim 1$ TeV.

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.74±0.33) %	
Γ_2	$e^+\nu$		(10.9 ±0.4) %	
Γ_3	$\mu^+\nu$		(10.2 ±0.5) %	
Γ_4	$\tau^+\nu$		(11.3 ±0.8) %	
Γ_5	hadrons		(67.8 ±1.0) %	
Γ_6	$\pi^+\gamma$		< 2.2 × 10^{-4}	95%

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

CONSTRAINED FIT INFORMATION

Overall fits are performed to determine the branching ratios of the *W*. For each LEP experiment the correlation matrix of the leptonic branching ratios is used. A first fit determines three individual leptonic branching ratios, $B(W \to e\nu_e)$, $B(W \to \mu\nu_\mu)$, and $B(W \to \tau\nu_\tau)$. This fit has a $\chi^2 = 9.0$ for 17 degrees of freedom. The second fit assumes lepton universality and determines the leptonic branching ratio $B(W \to \ell\nu_\ell)$, from which one also derives the hadronic branching ratio, assuming $B(W \to \text{hadrons}) = 1\text{–}3 \cdot B(W \to \ell\nu_\ell)$. This fit has a $\chi^2 = 10.9$ for 19 degrees of freedom.

W BRANCHING RATIOS

The LEP collaborations obtain the *W* branching ratios by a fit to their measured cross sections of the final states $e^+e^- \to W^+W^- \to q\overline{q}e\nu_e$, $q\overline{q}\mu\nu_\mu$, $q\overline{q}\tau\nu_\tau$, $q\overline{q}q\overline{q}$, $\ell\nu_\ell\ell\nu_\ell$. The leptonic branching ratios and $\sigma(e^+e^- \to W^+W^-)$ at the respective center-of-mass energies are the fitted parameters. Two fits are performed, one without and one assuming lepton universality. The hadronic branching ratio is derived from the second fit assuming $B(W \to \text{hadrons}) = 1\text{–}3 \cdot B(W \to \ell\nu_\ell)$.

$\Gamma(\ell^+\nu)/\Gamma_{\rm total}$ — Γ_1/Γ

ℓ indicates average over e, μ, and τ modes, not sum over modes.

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.1074±0.0033 OUR FIT					
0.108 ±0.005 OUR AVERAGE					
0.113 ±0.012 ±0.003	avg	52	ABREU	98B DLPH	$E_{\rm cm}^{ee}$= 161.3 + 172.14 GeV
$0.101^{+0.011}_{-0.010}$ ±0.002	avg	61	ACKERSTAFF	98D OPAL	$E_{\rm cm}^{ee}$= 161.3 + 172.12 GeV
$0.119^{+0.013}_{-0.012}$ ±0.002	avg	51	ACCIARRI	97M L3	$E_{\rm cm}^{ee}$= 161.3 + 172.13 GeV
0.104 ±0.008	avg	3642	[45] ABE	92I CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV

[45] $1216 \pm 38^{+27}_{-31}$ $W \to \mu\nu$ events from ABE 92I and 2426 $W \to e\nu$ events of ABE 91C. ABE 92I give the inverse quantity as 9.6 ± 0.7 and we have inverted.

$\Gamma(e^+\nu)/\Gamma_{\rm total}$ — Γ_2/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.109 ±0.004 OUR FIT					
0.109 ±0.004 OUR AVERAGE					
$0.102^{+0.038}_{-0.032}$ ±0.003	f&a	16	ABREU	98B DLPH	$E_{\rm cm}^{ee}$= 161.3 + 172.14 GeV
$0.098^{+0.022}_{-0.020}$ ±0.003	f&a	21	ACKERSTAFF	98D OPAL	$E_{\rm cm}^{ee}$= 161.3 + 172.12 GeV
$0.165^{+0.037}_{-0.033}$ ±0.005	f&a	23	ACCIARRI	97M L3	$E_{\rm cm}^{ee}$= 161.3 + 172.13 GeV
0.097 ±0.02 ±0.005	f&a	21	BARATE	97S ALEP	$E_{\rm cm}^{ee}$= 161.3 + 172.09 GeV
0.1094±0.0033±0.0031	f&a		[46] ABE	95W CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
0.10 ±0.014 $^{+0.02}_{-0.03}$	f&a	248	[47] ANSARI	87C UA2	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.106 ±0.0096		2426	[48] ABE	91C CDF	Repl. by ABE 94B
seen		299	[49] ALBAJAR	89 UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
seen		119	APPEL	86 UA2	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
seen		172	ARNISON	86 UA1	Repl. by ALBAJAR 89

[46] ABE 95W result is from a measurement of $\sigma B(W \to e\nu)/\sigma B(Z \to e^+e^-) = 10.90 \pm 0.32 \pm 0.29$, the theoretical prediction for the cross section ratio, the experimental knowledge of $\Gamma(Z \to e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$.

[47] The first error was obtained by adding the statistical and systematic experimental uncertainties in quadrature. The second error reflects the dependence on theoretical prediction of total *W* cross section: $\sigma(546\ \text{GeV}) = 4.7^{+1.4}_{-0.7}$ nb and $\sigma(630\ \text{GeV}) = 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[48] ABE 91C result is from a measurement of $\sigma B(W \to e\nu)/\sigma B(Z \to e^+e^-)$, the theoretical prediction for the cross section ratio, and the experimental knowledge of $\Gamma(Z \to e^+e^-)/\Gamma(Z \to \text{all})$.

[49] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

$\Gamma(\mu^+\nu)/\Gamma_{\rm total}$ — Γ_3/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.102±0.005 OUR FIT					
0.097±0.007 OUR AVERAGE					
$0.107^{+0.032}_{-0.027}$±0.003	f&a	20	ABREU	98B DLPH	$E_{\rm cm}^{ee}$= 161.3 + 172.14 GeV
$0.073^{+0.019}_{-0.017}$±0.002	f&a	16	ACKERSTAFF	98D OPAL	$E_{\rm cm}^{ee}$= 161.3 + 172.12 GeV
$0.084^{+0.028}_{-0.024}$±0.003	f&a	13	ACCIARRI	97M L3	$E_{\rm cm}^{ee}$= 161.3 + 172.13 GeV
0.112±0.02 ±0.006	f&a	25	BARATE	97S ALEP	$E_{\rm cm}^{ee}$= 161.3 + 172.09 GeV
0.10 ±0.01	f&a	1216	[50] ABE	92I CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV

[50] ABE 92I quote the inverse quantity as 9.9 ± 1.2 which we have inverted.

$\Gamma(\tau^+\nu)/\Gamma_{\rm total}$ — Γ_4/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.113±0.008 OUR FIT					
0.124±0.017 OUR AVERAGE					
$0.134^{+0.050}_{-0.048}$±0.007	f&a	16	ABREU	98B DLPH	$E_{\rm cm}^{ee}$= 161.3 + 172.14 GeV
$0.140^{+0.030}_{-0.028}$±0.005	f&a	23	ACKERSTAFF	98D OPAL	$E_{\rm cm}^{ee}$= 161.3 + 172.12 GeV
$0.109^{+0.042}_{-0.039}$±0.005	f&a	15	ACCIARRI	97M L3	$E_{\rm cm}^{ee}$= 161.3 + 172.13 GeV
0.113±0.027±0.006	f&a	37	BARATE	97S ALEP	$E_{\rm cm}^{ee}$= 161.3 + 172.09 GeV

$\Gamma(\text{hadrons})/\Gamma_{\rm total}$ — Γ_5/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.678±0.010 OUR FIT					
0.672±0.017 OUR AVERAGE					
$0.660^{+0.036}_{-0.037}$±0.009	avg	57	ABREU	98B DLPH	$E_{\rm cm}^{ee}$= 161.3 + 172.14 GeV
$0.698^{+0.030}_{-0.032}$±0.007	avg	52	ACKERSTAFF	98D OPAL	$E_{\rm cm}^{ee}$= 161.3 + 172.12 GeV
$0.642^{+0.037}_{-0.038}$±0.005	avg	70	ACCIARRI	97M L3	$E_{\rm cm}^{ee}$= 161.3 + 172.13 GeV
0.677±0.031±0.007	avg	65	BARATE	97S ALEP	$E_{\rm cm}^{ee}$= 161.3 + 172.09 GeV

$\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ — Γ_3/Γ_2

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.94±0.05 OUR FIT					
0.97±0.06 OUR AVERAGE					
0.89±0.10	f&a	13k	[51] ABACHI	95D D0	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
1.02±0.08	f&a	1216	[52] ABE	92I CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.00±0.14±0.08		67	ALBAJAR	89 UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
$1.24^{+0.6}_{-0.4}$		14	ARNISON	84D UA1	Repl. by ALBAJAR 89

[51] ABACHI 95D obtain this result from the measured $\sigma_W B(W \to \mu\nu)= 2.09 \pm 0.23 \pm 0.11$ nb and $\sigma_W B(W \to e\nu)= 2.36 \pm 0.07 \pm 0.13$ nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.

[52] ABE 92I obtain $\sigma_W B(W \to \mu\nu)= 2.21 \pm 0.07 \pm 0.21$ and combine with ABE 91C σ_W B(($W \to e\nu$)) to give a ratio of the couplings from which we derive this measurement.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_4/Γ_2

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
1.03 ±0.07 OUR FIT						
1.00 ±0.08 OUR AVERAGE						
0.94 ±0.14	f&a	179	[53] ABE	92E	CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
1.04 ±0.08 ±0.08	f&a	754	[54] ALITTI	92F	UA2	$E_{\rm cm}^{p\overline{p}}$= 630 GeV
1.02 ±0.20 ±0.12	f&a	32	ALBAJAR	89	UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.995±0.112±0.083		198	ALITTI	91C	UA2	Repl. by ALITTI 92F
1.02 ±0.20 ±0.10		32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

[53] ABE 92E use two procedures for selecting $W \to \tau\nu_\tau$ events. The missing E_T trigger leads to $132 \pm 14 \pm 8$ events and the τ trigger to $47 \pm 9 \pm 4$ events. Proper statistical and systematic correlations are taken into account to arrive at $\sigma B(W \to \tau\nu) = 2.05 \pm 0.27$ nb. Combined with ABE 91C result on $\sigma B(W \to e\nu)$, ABE 92E quote a ratio of the couplings from which we derive this measurement.

[54] This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

$\Gamma(\pi^+\gamma)/\Gamma(e^+\nu)$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 2.0 × 10⁻³	95	ABE	96I	CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV
< 4.9 × 10⁻³	95	[55] ALITTI	92D	UA2	$E_{\rm cm}^{p\overline{p}}$= 630 GeV
<58 × 10⁻³	95	[56] ALBAJAR	90	UA1	$E_{\rm cm}^{p\overline{p}}$= 546, 630 GeV

[55] ALITTI 92D limit is 3.8×10^{-3} at 90%CL.

[56] ALBAJAR 90 obtain < 0.048 at 90%CL.

W REFERENCES

ABREU	98B	EPJ C1 (accepted) CERN-PPE/97-160	P. Abreu+	(DELPHI Collab.)
ACKERSTAFF	98D	EPJ C1 395	K. Ackerstaff+	(OPAL Collab.)
BARATE	98B	PL B422 384	R. Barate+	(ALEPH Collab.)
ABREU	97	PL B397 158	+Adam, Adye, Adzic+	(DELPHI Collab.)
ACCIARRI	97	PL B398 223	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	97M	PL B407 419	M. Acciarri+	(L3 Collab.)
ACCIARRI	97S	PL B413 176	M. Acciarri+	(L3 Collab.)
BARATE	97	PL B401 347	+Buskulic, Decamp, Ghez+	(ALEPH Collab.)
BARATE	97S	PL B415 435	R. Barate+	(ALEPH Collab.)
ABACHI	96E	PRL 77 3309	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	96I	PRL 76 2852	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ACKERSTAFF	96B	PL B389 416	+Alexander, Allison, Altekamp+	(OPAL Collab.)
AID	96D	PL B379 319	+Andreev, Andrieu, Appuhn+	(H1 Collab.)
ABACHI	95D	PRL 75 1456	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	95C	PRL 74 341	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95G	PRL 74 1936	+Albrow, Amidei, Antos+	(CDF Collab.)
ABE	95P	PRL 75 11	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
Also	95Q	PR D52 4784	Abe, Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95W	PR D52 2624	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
Also	94B	PRL 73 220	Abe, Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABE	94B	PRL 73 220	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ROSNER	94	PR D49 1363	+Worah, Takeuchi	(EFI, FNAL)
ABE	92E	PRL 68 3398	+Amidei, Apollinari, Atac+	(CDF Collab.)
ABE	92I	PRL 69 28	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALITTI	92	PL B276 365	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92C	PL B277 194	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92D	PL B277 203	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92F	PL B280 137	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
SAMUEL	92	PL B280 124	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	+Ambrosini, Ansari, Autiero+	(UA2 Collab.)
SAMUEL	91	PRL 67 9	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
Also	91C	PRL 67 2920 erratum		
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	91C	PR D44 29	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91B	PR D43 2070	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	90	PL B241 283	+Albrow, Allkofer+	(UA1 Collab.)
ALITTI	90B	PL B241 150	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
ABE	89I	PRL 62 1005	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BAUR	88	NP B308 127	+Zeppenfeld	(FSU, WISC)
GRIFOLS	88	IJMP A3 225	+Peris, Sola	(BARC, DESY)
Also	87	PL B197 437	Grifols, Peris, Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
GROTCH	87	PR D36 2153	+Robinett	(PSU)
HAGIWARA	87	NP B282 253	+Peccei, Zeppenfeld, Hikasa	(KEK, UCLA, FSU)
VANDERBIJ	87	PR D35 1088	van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.)
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
GRAU	85	PL 154B 283	+Grifols	(BARC)
SUZUKI	85	PL 153B 289		(LBL)
ARNISON	84D	PL 134B 469	+Astbury, Aubert, Bacci+	(UA1 Collab.)
HERZOG	84	PL 148B 355		(WISC)
Also	84B	PL 155B 468 erratum	Herzog	(WISC)
ARNISON	83	PL 122B 103	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BANNER	83B	PL 122B 476	+Battiston, Bloch, Bonaudi+	(UA2 Collab.)

Z

$J = 1$

THE Z BOSON

Revised February 1998 by C. Caso (Univ. of Genova) and A. Gurtu (Tata Inst.)

Precision measurements at the Z-boson resonance using electron–positron colliding beams began in 1989 at the SLC and at LEP. During 1989–95, the four CERN experiments have made high-statistics studies of the Z. The availability of longitudinally polarized electron beams at the SLC since 1993 has enabled a precision determination of the effective electroweak mixing angle $\sin^2\overline{\theta}_W$ that is competitive with the CERN results on this parameter.

The Z-boson properties reported in this section may broadly be categorized as:

- The standard 'lineshape' parameters of the Z consisting of its mass, M_Z, its total width, Γ_Z, and its partial decay widths, Γ(hadrons), and $\Gamma(\ell\ell)$ where $\ell = e, \mu, \tau, \nu$;
- Z asymmetries in leptonic decays and extraction of Z couplings to charged and neutral leptons;
- The b- and c-quark-related partial widths and charge asymmetries which require special techniques;
- Determination of Z decay modes and the search for modes that violate known conservation laws;
- Average particle multiplicities in hadronic Z decay.

For the lineshape-related Z properties there are no new published LEP results after those included in the 1994 edition of this compilation. The reason for this is the identification in mid 1995 of a new systematic effect which shifts the LEP energy by a few MeV. This is due to a drift of the dipole field in the LEP magnets caused by parasitic currents generated by electrically powered trains in the Geneva area. The LEP Energy Working Group has been studying the implications of this for the Z-lineshape properties which would be obtained after analysis of the high statistics 1993–95 data. The main consequence of this effect is expected to be in the determination of the Z mass.

Details on Z-parameter determination and the study of $Z \to b\overline{b}, c\overline{c}$ at LEP and SLC are given in this note.

The standard 'lineshape' parameters of the Z are determined with increasing precision from an analysis of the production cross sections of these final states in e^+e^- collisions. The $Z \to \nu\overline{\nu}(\gamma)$ state is identified directly by detecting single photon production and indirectly by subtracting the visible partial widths from the total width. Inclusion in this analysis of the forward-backward asymmetry of charged leptons, $A_{FB}^{(0,\ell)}$, of the τ polarization, $P(\tau)$, and its forward-backward asymmetry, $P(\tau)^{fb}$, enables the separate determination of the effective vector ($\overline{g}_V$) and axial vector ($\overline{g}_A$) couplings of the Z to these leptons and the ratio ($\overline{g}_V/\overline{g}_A$) which is related to the effective electroweak mixing angle $\sin^2\overline{\theta}_W$ (see the "Electroweak Model and Constraints on New Physics" Review).

Determination of the b- and c-quark-related partial widths and charge asymmetries involves tagging the b and c quarks. Traditionally this was done by requiring the presence of a prompt lepton in the event with high momentum and high transverse momentum (with respect to the accompanying jet). Precision vertex measurement with silicon detectors has enabled one to do impact parameter and lifetime tagging. Neural-network techniques have also been used to classify events as b or non-b on a statistical basis using event–shape variables. Finally, the presence of a charmed meson (D/D^*) has been used to tag heavy quarks.

Z-parameter determination

LEP is run at a few energy points on and around the Z mass constituting an energy 'scan.' The shape of the cross-section variation around the Z peak can be described by a Breit-Wigner *ansatz* with an energy-dependent total width [1–3]. The **three** main properties of this distribution, viz., the **position** of the peak, the **width** of the distribution, and the **height** of the peak, determine respectively the values of M_Z, Γ_Z, and $\Gamma(e^+e^-) \times \Gamma(f\overline{f})$, where $\Gamma(e^+e^-)$ and $\Gamma(f\overline{f})$ are the electron and fermion partial widths of the Z. The quantitative determination of these parameters is done by writing analytic expressions for these cross sections in terms of the parameters and fitting the calculated cross sections to the measured ones by varying these parameters, taking properly into account all the errors. Single-photon exchange (σ^0_γ) and γ-Z interference ($\sigma^0_{\gamma Z}$) are included, and the large (~25 %) initial-state radiation (ISR) effects are taken into account by convoluting the analytic expressions over a 'Radiator Function' [1–4] $H(s,s')$. Thus for the process $e^+e^- \to f\overline{f}$:

$$\sigma_f(s) = \int H(s,s')\,\sigma^0_f(s')\,ds' \tag{1}$$

$$\sigma^0_f(s) = \sigma^0_Z + \sigma^0_\gamma + \sigma^0_{\gamma Z} \tag{2}$$

$$\sigma^0_Z = \frac{12\pi}{M^2_Z}\,\frac{\Gamma(e^+e^-)\Gamma(f\overline{f})}{\Gamma^2_Z}\,\frac{s\,\Gamma^2_Z}{(s-M^2_Z)^2 + s^2\Gamma^2_Z/M^2_Z} \tag{3}$$

$$\sigma^0_\gamma = \frac{4\pi\alpha^2(s)}{3s}\,Q^2_f N^f_c \tag{4}$$

$$\begin{aligned}\sigma^0_{\gamma Z} &= -\frac{2\sqrt{2}\alpha(s)}{3}\,(Q_f G_F N^f_c g_{Ve} g_{Vf}) \\ &\times \frac{(s-M^2_Z)M^2_Z}{(s-M^2_Z)^2 + s^2\Gamma^2_Z/M^2_Z}\end{aligned} \tag{5}$$

where Q_f is the charge of the fermion, $N^f_c = 3(1)$ for quark (lepton) and g_{Vf} is the neutral vector coupling of the Z to the fermion-antifermion pair $f\overline{f}$.

Since $\sigma^0_{\gamma Z}$ is expected to be much less than σ^0_Z, the LEP Collaborations have generally calculated the interference term in the framework of the Standard Model using the best known values of g_V. This fixing of $\sigma^0_{\gamma Z}$ leads to a tighter constraint on M_Z and consequently a smaller error on its fitted value.

Defining

$$A_f = 2\frac{g_{Vf}\cdot g_{Af}}{(g^2_{Vf} + g^2_{Af})} \tag{6}$$

where g_{Af} is the neutral axial-vector coupling of the Z to $f\overline{f}$, the lowest-order expressions for the various lepton-related asymmetries on the Z pole are [5–7] $A^{(0,\ell)}_{FB} = (3/4)A_e A_f$, $P(\tau) = -A_\tau$, $P(\tau)^{fb} = -(3/4)A_e$, $A_{LR} = A_e$. The full analysis takes into account the energy dependence of the asymmetries. Experimentally A_{LR} is defined as $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ where $\sigma_{L(R)}$ are the $e^+e^- \to Z$ production cross sections with left- (right)-handed electrons.

In terms of g_A and g_V, the partial decay width of the Z to $f\overline{f}$ can be written as

$$\Gamma(f\overline{f}) = \frac{G_F M^3_Z}{6\sqrt{2}\pi}\,(g^2_{Vf} + g^2_{Af})\,N^f_c(1+\delta_{\rm QED})(1+\delta_{\rm QCD}) \tag{7}$$

where $\delta_{\rm QED} = 3\alpha Q^2_f/4\pi$ accounts for final-state photonic corrections and $\delta_{\rm QCD} = 0$ for leptons and $\delta_{\rm QCD} = (\alpha_s/\pi) + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3$ for quarks, α_s being the strong coupling constant at $\mu = M_Z$.

In the above framework, the QED radiative corrections have been explicitly taken into account by convoluting over the ISR and allowing the electromagnetic coupling constant to run [8]: $\alpha(s) = \alpha/(1-\Delta\alpha)$. On the other hand, weak radiative corrections that depend upon the assumptions of the electroweak theory and on the values of the unknown $M_{\rm top}$ and $M_{\rm Higgs}$ are accounted for by **absorbing them into the couplings**, which are then called the *effective* couplings $\overline{g}_V$ and $\overline{g}_A$ (or alternatively the effective parameters of the ⋆ scheme of Kennedy and Lynn [9]).

S-matrix approach to the Z

While practically all experimental analyses of LEP/SLC data have followed the 'Breit-Wigner' approach described above, an alternative S-matrix-based analysis is also possible. The Z, like all unstable particles, is associated with a complex pole in the S matrix. The pole position is process independent and gauge invariant. The mass, $\overline{M}_Z$, and width, $\overline{\Gamma}_Z$, can be defined in terms of the pole in the energy plane via [10–13]

$$\overline{s} = \overline{M}^2_Z - i\overline{M}_Z\overline{\Gamma}_Z \tag{8}$$

leading to the relations

$$\begin{aligned}\overline{M}_Z &= M_Z/\sqrt{1+\Gamma^2_Z/M^2_Z} \\ &\approx M_Z\ - 34.1\ \text{MeV}\end{aligned} \tag{9}$$

$$\begin{aligned}\overline{\Gamma}_Z &= \Gamma_Z/\sqrt{1+\Gamma^2_Z/M^2_Z} \\ &\approx \Gamma_Z\ - 0.9\ \text{MeV}\ .\end{aligned} \tag{10}$$

Some authors [14] choose to define the Z mass and width via

$$\overline{s} = (\overline{M}_Z - \frac{i}{2}\overline{\Gamma}_Z)^2 \tag{11}$$

which yields $\overline{M}_Z \approx M_Z - 26$ MeV, $\overline{\Gamma}_Z \approx \Gamma_Z - 1.2$ MeV.

The L3 and OPAL Collaborations at LEP (ACCIARRI 97K and ACKERSTAFF 97C) have analyzed their data using the S–matrix approach as defined in Eq. (8), in addition to the conventional one. They observe a downward shift in the Z mass as expected.

Handling the large-angle e^+e^- final state

Unlike other $f\overline{f}$ decay final states of the Z, the e^+e^- final state has a contribution not only from the s-channel but also from the t-channel and s-t interference. The full amplitude is not amenable to fast calculation, which is essential if one has to carry out minimization fits within reasonable computer time. The usual procedure is to calculate the non-s channel part of the cross section separately using the Standard Model programs ALIBABA [15] or TOPAZ0 [16] with the measured value of M_{top}, and the 'central' value of M_{Higgs} (300 GeV) and add it to the s-channel cross section calculated as for other channels. This leads to two additional sources of error in the analysis: firstly, the theoretical calculation in ALIBABA itself is known to be accurate to ~ 0.5%, and secondly, there is uncertainty due to the error on M_{top} and the unknown value of M_{Higgs} (60–1000 GeV). These additional errors are propagated into the analysis by including them in the systematic error on the e^+e^- final state.

Errors due to uncertainty in LEP energy determination [17–21]

The systematic errors related to the LEP energy measurement can be classified as:

- The absolute energy scale error;
- Energy-point-to-energy-point errors due to the non-linear response of the magnets to the exciting currents;
- Energy-point-to-energy-point errors due to possible higher-order effects in the relationship between the dipole field and beam energy;
- Energy reproducibility errors due to various unknown uncertainties in temperatures, tidal effects, corrector settings, RF status, *etc.* Since one groups together data taken at 'nominally same' energies in different fills, it can be assumed that these errors are uncorrelated and are reduced by $\sqrt{N_{\text{fill}}}$ where N_{fill} is the (luminosity weighted) effective number of fills at a particular energy point.

At each energy point the last two errors can be summed into one point-to-point error.

Choice of fit parameters

The LEP Collaborations have chosen the following primary set of parameters for fitting: M_Z, Γ_Z, σ^0_{hadron}, $R(\text{lepton})$, $A^{(0,\ell)}_{FB}$, where $R(\text{lepton}) = \Gamma(\text{hadrons})/\Gamma(\text{lepton})$, $\sigma^0_{\text{hadron}} = 12\pi\Gamma(e^+e^-)\Gamma(\text{hadrons})/M^2_Z\Gamma^2_Z$. With a knowledge of these fitted parameters and their covariance matrix, any other parameter can be derived. The main advantage of these parameters is that they form the **least correlated** set of parameters, so that it becomes easy to combine results from the different LEP experiments.

Thus, the most general fit carried out to cross section and asymmetry data determines the **nine parameters**: M_Z, Γ_Z, σ^0_{hadron}, $R(e)$, $R(\mu)$, $R(\tau)$, $A^{(0,e)}_{FB}$, $A^{(0,\mu)}_{FB}$, $A^{(0,\tau)}_{FB}$. Assumption of lepton universality leads to a **five-parameter fit** determining M_Z, Γ_Z, σ^0_{hadron}, $R(\text{lepton})$, $A^{(0,\ell)}_{FB}$. The use of **only** cross-section data leads to six- or four-parameter fits if lepton universality is or is not assumed, *i.e.*, $A^{(0,\ell)}_{FB}$ values are not determined.

In order to determine the best values of the effective vector and axial vector couplings of the charged leptons to the Z, the above mentioned nine- and five-parameter fits are carried out with added constraints from the measured values of A_τ and A_e obtained from τ polarization studies at LEP and the determination of A_{LR} at SLC.

Combining results from the LEP and SLC experiments [22]

Each LEP experiment provides the values of the parameters mentioned above together with the full covariance matrix. The statistical and experimental systematic errors are assumed to be uncorrelated among the four experiments. The sources of **common** systematic errors are i) the LEP energy uncertainties, and ii) the effect of theoretical uncertainty in calculating the small-angle Bhabha cross section for luminosity determination and in estimating the non-s channel contribution to the large-angle Bhabha cross section. Using this information, a full covariance matrix, V, of all the input parameters is constructed and a combined parameter set is obtained by minimizing $\chi^2 = \Delta^T V^{-1} \Delta$, where Δ is the vector of residuals of the combined parameter set to the results of individual experiments.

Non-LEP measurement of a Z parameter, (*e.g.*, $\Gamma(e^+e^-)$ from SLD) is included in the overall fit by calculating its value using the fit parameters and constraining it to the measurement.

Study of $Z \rightarrow b\overline{b}$ and $Z \rightarrow c\overline{c}$

In the sector of c- and b-physics the LEP experiments have measured the ratios of partial widths $R_b = \Gamma(Z \rightarrow b\overline{b})/\Gamma(Z \rightarrow \text{hadrons})$ and $R_c = \Gamma(Z \rightarrow c\overline{c})/\Gamma(Z \rightarrow \text{hadrons})$ and the forward-backward (charge) asymmetries $A^{b\overline{b}}_{FB}$ and $A^{c\overline{c}}_{FB}$. Several of the analyses have also determined other quantities, in particular the semileptonic branching ratios, $\text{B}(b \rightarrow \ell)$ and $\text{B}(b \rightarrow c \rightarrow \ell^+)$, the average $B^0\overline{B}^0$ mixing parameter $\overline{\chi}$ and the probabilities for a c-quark to fragment into a D^+, a D_s, a D^{*+} , or a charmed baryon. The latter measurements do not concern properties of the Z boson and hence they are not covered in this section. However, they are correlated with the electroweak parameters, and since the mixture of b hadrons is different from the one at the $\Upsilon(4S)$, their values might differ from those measured at the $\Upsilon(4S)$.

All the above quantities are correlated to each other since:

- Several analyses (for example the lepton fits) determine more than one parameter simultaneously;
- Some of the electroweak parameters depend explicitly on the values of other parameters (for example R_b depends on R_c);
- Common tagging and analysis techniques produce common systematic uncertainties.

The LEP Electroweak Heavy Flavour Working Group has developed [23] a procedure for combining the measurements taking into account known sources of correlation. The combining procedure determines eleven parameters: the four parameters of interest in the electroweak sector, R_b, R_c, $A_{FB}^{b\bar{b}}$, and $A_{FB}^{c\bar{c}}$ and, in addition, $\mathrm{B}(b \to \ell)$, $\mathrm{B}(b \to c \to \ell^+)$, $\overline{\chi}$, $f(D^+)$, $f(D_s)$, $f(c_{\mathrm{baryon}})$ and $P(c \to D^{*+}) \times \mathrm{B}(D^{*+} \to \pi^+ D^0)$, to take into account their correlations with the electroweak parameters. Before the fit both the peak and off-peak asymmetries are translated to $\sqrt{s} = 91.26$ GeV using the predicted dependence from ZFITTER [4].

Summary of the measurements and of the various kinds of analysis

The measurements of R_b and R_c fall into two classes. In the first, named single-tag measurement, a method for selecting b and c events is applied and the number of tagged events is counted. The second technique, named double-tag measurement, is based on the following principle: if the number of events with a single hemisphere tagged is N_t and with both hemispheres tagged is N_{tt}, then given a total number of N_{had} hadronic Z decays one has:

$$\frac{N_t}{2N_{\mathrm{had}}} = \varepsilon_b R_b + \varepsilon_c R_c + \varepsilon_{uds}(1 - R_b - R_c) \tag{12}$$

$$\frac{N_{tt}}{N_{\mathrm{had}}} = C_b \varepsilon_b^2 R_b + C_c \varepsilon_c^2 R_c + C_{uds} \varepsilon_{uds}^2 (1 - R_b - R_c) \tag{13}$$

where ε_b, ε_c, and ε_{uds} are the tagging efficiencies per hemisphere for b, c, and light quark events, and $C_q \neq 1$ accounts for the fact that the tagging efficiencies between the hemispheres may be correlated. In tagging the b one has $\varepsilon_b \gg \varepsilon_c \gg \varepsilon_{uds}$, $C_b \approx 1$. Neglecting the c and uds background and the hemisphere correlations, these equations give:

$$\varepsilon_b = 2N_{tt}/N_t \tag{14}$$

$$R_b = N_t^2/(4N_{tt}N_{\mathrm{had}}) \, . \tag{15}$$

The double-tagging method has thus the great advantage that the tagging efficiency is directly derived from the data, reducing the systematic error of the measurement. The backgrounds, dominated by $c\bar{c}$ events, obviously complicate this simple picture, and their level must still be inferred by other means. The rate of charm background in these analyses depends explicitly on the value of R_c. The correlations in the tagging efficiencies between the hemispheres (due for instance to correlations in momentum between the b hadrons in the two hemispheres) are small but nevertheless lead to further systematic uncertainties.

The measurements in the b- and c-sector can be grouped in the following categories:

- Lepton fits which use hadronic events with one or more leptons in the final state. Each analysis usually gives several electroweak parameters chosen among: R_b, R_c, $A_{FB}^{b\bar{b}}$, $A_{FB}^{c\bar{c}}$, $\mathrm{B}(b \to \ell)$, $\mathrm{B}(b \to c \to \ell^+)$ and $\overline{\chi}$. The output parameters are then correlated. The dominant sources of systematics are due to lepton identification, to other semileptonic branching ratios and to the modelling of the semileptonic decay;
- Event shape tag for R_b;
- Lifetime (and lepton) double-tagging measurements of R_b. These are the most precise measurements of R_b and obviously dominate the combined result. The main sources of systematics come from the charm contamination and from estimating the hemisphere b-tagging efficiency correlation. The charm rejection has been improved (and hence the systematic errors reduced) by using either the information of the secondary vertex invariant mass or the information from the energy of all particles at the secondary vertex and their rapidity;
- Measurements of $A_{FB}^{b\bar{b}}$ using lifetime tagged events with a hemisphere charge measurement. Their contribution to the combined result has roughly the same weight as the lepton fits;
- Analyses with $D/D^{*\pm}$ to measure R_c. These measurements make use of several different tagging techniques (inclusive/exclusive double tag, inclusive single/double tag, exclusive double tag, reconstruction of all weakly decaying D states) and no assumptions are made on the energy dependence of charm fragmentation;
- Analyses with $D/D^{*\pm}$ to measure $A_{FB}^{c\bar{c}}$ or simultaneously $A_{FB}^{b\bar{b}}$ and $A_{FB}^{c\bar{c}}$;
- Measurements of A_b and A_c from SLD, using several tagging methods (lepton, D/D^*, and impact parameter). These quantities are directly extracted from a measurement of the left-right forward-backward asymmetry in $c\bar{c}$ and $b\bar{b}$ production using a polarized electron beam.

Averaging procedure

All the measurements are provided by the LEP Collaborations in the form of tables with a detailed breakdown of the systematic errors of each measurement and its dependence on other electroweak parameters.

The averaging proceeds via the following steps:

- Define and propagate a consistent set of external inputs such as branching ratios, hadron lifetimes, fragmentation models *etc.* All the measurements are also consistently checked to ensure that all use a common set of assumptions (for instance since the QCD corrections for the forward–backward asymmetries are strongly dependent on the experimental conditions, the data are corrected before combining);
- Form the full (statistical and systematic) covariance matrix of the measurements. The systematic correlations between different analyses are calculated from the detailed error breakdown in the measurement tables. The correlations relating several measurements made by the same analysis are also used;
- Take into account any explicit dependence of a measurement on the other electroweak parameters. As an example of this dependence we illustrate the case of the double-tag measurement of R_b, where c-quarks constitute the main background. The normalization of the charm contribution is not usually fixed by the data and the measurement of R_b depends on the assumed value of R_c, which can be written as:

$$R_b = R_b^{\mathrm{meas}} + a(R_c)\frac{(R_c - R_c^{\mathrm{used}})}{R_c} , \qquad (16)$$

  where R_b^{meas} is the result of the analysis which assumed a value of $R_c = R_c^{\mathrm{used}}$ and $a(R_c)$ is the constant which gives the dependence on R_c;
- Perform a χ^2 minimization with respect to the combined electroweak parameters.

After the fit the average peak asymmetries $A_{FB}^{c\bar{c}}$ and $A_{FB}^{b\bar{b}}$ are corrected for the energy shift and for QED, γ exchange, and γZ interference effects to obtain the corresponding pole asymmetries $A_{FB}^{0,c}$ and $A_{FB}^{0,b}$. A small correction is also applied to both R_b and R_c to account for the contribution of γ exchange.

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Z MASS

The fit is performed using the *Z* mass and width, the *Z* hadronic pole cross section, the ratios of hadronic to leptonic partial widths, and the *Z* pole forward-backward lepton asymmetries. We believe that this set is the most free of correlations. Common systematic errors are taken into account. For more details, see the 'Note on the *Z* Boson.'

The *Z*-boson mass listed here corresponds to a Breit-Wigner resonance parameter. The value is 34 MeV greater than the real part of the position of the pole (in the energy-squared plane) in the *Z*-boson propagator. Also the LEP experiments have generally assumed a fixed value of the $\gamma - Z$ interferences term based on the standard model. Keeping this term as free parameter leads to a somewhat larger error on the fitted *Z* mass. See ACCIARRI 97K and ACKERSTAFF 97C for a detailed investigation of both these issues.

A new source of LEP energy variation was discovered in mid 1995: an energy change of a few MeV is correlated with the passage of a train on nearby railway tracks. The LEP energy working group is studying the implications of this effect for the high statistics data recorded since 1993. The main consequence of this is expected to be a shift in the overall LEP energy values leading to a corresponding shift in the value of m_Z. The LEP collaborations have consequently deferred publication of their results on *Z* lineshape and lepton forward-backward asymmetries based on 1993 and later data.

Because of the high current interest, we mention here the following preliminary results, but do not average them or include them in the Listings or Tables.

Combining published and unpublished preliminary LEP results (as of end of February 1998) yields an average *Z*-boson mass of 91.1867 ± 0.0020 GeV, with a total width of 2.4948 ± 0.0025 GeV.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
91.187±0.007 OUR FIT					
91.188±0.007 OUR AVERAGE					
91.187±0.007±0.006	1.16M	[1] ABREU	94	DLPH	E_{cm}^{ee}= 88–94 GeV
91.195±0.006±0.007	1.19M	[1] ACCIARRI	94	L3	E_{cm}^{ee}= 88–94 GeV
91.182±0.007±0.006	1.33M	[1] AKERS	94	OPAL	E_{cm}^{ee}= 88–94 GeV
91.187±0.007±0.006	1.27M	[1] BUSKULIC	94	ALEP	E_{cm}^{ee}= 88–94 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

91.193 ± 0.010	1.2M	[2] ACCIARRI	97K	L3	$E^{ee}_{\rm cm}$ = LEP1 + 130–136 GeV + 161–172 GeV
91.185 ± 0.010		[3] ACKERSTAFF	97C	OPAL	$E^{ee}_{\rm cm}$ = LEP1 + 130–136 GeV + 161 GeV
91.162 ± 0.011	1.2M	[4] ACCIARRI	96B	L3	Repl. by ACCIARRI 97K
91.192 ± 0.011	1.33M	[5] ALEXANDER	96X	OPAL	Repl. by ACKERSTAFF 97C
91.151 ± 0.008		[6] MIYABAYASHI	95	TOPZ	$E^{ee}_{\rm cm}$ = 57.8 GeV
$91.181\pm0.007\pm0.006$	512k	[7] ACTON	93D	OPAL	Repl. by AKERS 94
91.195 ± 0.009	460k	[8] ADRIANI	93F	L3	Repl. by ACCIARRI 94
91.187 ± 0.009	520k	[9] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
$91.74\ \pm0.28\ \pm0.93$	156	[10] ALITTI	92B	UA2	$E^{p\overline{p}}_{\rm cm}$ = 630 GeV
$89.2\ ^{+2.1}_{-1.8}$		[11] ADACHI	90F	RVUE	
$90.9\ \pm0.3\ \pm0.2$	188	[12] ABE	89C	CDF	$E^{p\overline{p}}_{\rm cm}$ = 1.8 TeV
$91.14\ \pm0.12$	480	[13] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm}$ = 89–93 GeV
$93.1\ \pm1.0\ \pm3.0$	24	[14,15] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$ = 546,630 GeV

[1] The second error of 6.3 MeV is due to a common LEP energy uncertainty.

[2] ACCIARRI 97K interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix formalism with a combined fit to their cross section and asymmetry data at the Z peak (ACCIARRI 94) and their data at 130, 136, 161, and 172 GeV. The authors have corrected the measurement for the 34.1 MeV shift with respect to the Breit-Wigner fits. The error contains a contribution of ±3 MeV due to the uncertainty on the γZ interference.

[3] ACKERSTAFF 97C obtain this using the S-matrix formalism for a combined fit to their cross-section and asymmetry data at the Z peak (AKERS 94) and their data at 130, 136, and 161 GeV. The authors have corrected the measurement for the 34 MeV shift with respect to the Breit-Wigner fits.

[4] ACCIARRI 96B interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix ansatz. The 130–136 GeV data constrains the γZ interference terms. As expected, this result is below the mass values obtained with a standard Breit-Wigner parametrization.

[5] ALEXANDER 96X obtain this using the S-matrix formalism for a combined fit to their cross-section and asymmetry data at the Z peak (AKERS 94) and their data at 130 and 136 GeV. The authors have corrected the measurement for the 34 MeV shift with respect to the Breit-Wigner fits.

[6] MIYABAYASHI 95 combine their low energy total hadronic cross-section measurement with the ACTON 93D data and perform a fit using an S-matrix formalism. As expected, this result is below the mass values obtained with the standard Breit-Wigner parametrization.

[7] The systematic error in ACTON 93D is from the uncertainty in the LEP energy calibration.

[8] The error in ADRIANI 93F includes 6 MeV due to the uncertainty in LEP energy calibration.

[9] BUSKULIC 93J supersedes DECAMP 92B. The error includes 6 MeV due to the uncertainty in LEP energy calibration.

[10] Enters fit through W/Z mass ratio given in the W Particle Listings. The ALITTI 92B systematic error (±0.93) has two contributions: one (±0.92) cancels in m_W/m_Z and one (±0.12) is noncancelling. These were added in quadrature.

[11] ADACHI 90F use a Breit-Wigner resonance shape fit and combine their results with published data of PEP and PETRA.

[12] First error of ABE 89 is combination of statistical and systematic contributions; second is mass scale uncertainty.

[13] ABRAMS 89B uncertainty includes 35 MeV due to the absolute energy measurement.

[14] Enters fit through Z-W mass difference given in the W Particle Listings.

[15] ALBAJAR 89 result is from a total sample of 33 $Z \rightarrow e^+e^-$ events.

Z WIDTH

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.490 ± 0.007 OUR FIT					
2.491 ± 0.007 OUR AVERAGE					
$2.50\ \pm0.21\ \pm0.06$		[16] ABREU	96R	DLPH	$E^{ee}_{\rm cm}$ = 91.2 GeV
$2.483\pm0.011\pm0.0045$	1.16M	[17] ABREU	94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
$2.494\pm0.009\pm0.0045$	1.19M	[17] ACCIARRI	94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
$2.483\pm0.011\pm0.0045$	1.33M	[17] AKERS	94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
$2.501\pm0.011\pm0.0045$	1.27M	[17] BUSKULIC	94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.494 ± 0.010	1.2M	[18] ACCIARRI	97K	L3	$E^{ee}_{\rm cm}$ = LEP1 + 130–136 GeV + 161–172 GeV
2.492 ± 0.010	1.2M	[19] ACCIARRI	96B	L3	Repl. by ACCIARRI 97K
$2.483\pm0.011\pm0.004$	512k	[20] ACTON	93D	OPAL	Repl. by AKERS 94
2.490 ± 0.011	460k	[21] ADRIANI	93F	L3	Repl. by ACCIARRI 94
2.501 ± 0.012	520k	[22] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
$3.8\ \pm0.8\ \pm1.0$	188	ABE	89C	CDF	$E^{p\overline{p}}_{\rm cm}$ = 1.8 TeV
$2.42\ ^{+0.45}_{-0.35}$	480	[23] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm}$ = 89–93 GeV
$2.7\ ^{+1.2}_{-1.0}\ \pm1.3$	24	[24] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$ = 546,630 GeV
$2.7\ \pm2.0\ \pm1.0$	25	[25] ANSARI	87	UA2	$E^{p\overline{p}}_{\rm cm}$ = 546,630 GeV

[16] ABREU 96R obtain this value from a study of the interference between initial and final state radiation in the process $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$.

[17] The second error of 4.5 MeV is due to a common LEP energy uncertainty.

[18] ACCIARRI 97K interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix formalism with a combined fit to their cross section and asymmetry data at the Z peak (ACCIARRI 94) and their data at 130, 136, 161, and 172 GeV. The authors have corrected the measurement for the 0.9 MeV shift with respect to the Breit-Wigner fits.

[19] ACCIARRI 96B interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix ansatz. The 130–136 GeV data constrains the γZ interference terms. The fitted width is expected to be 0.9 MeV less than that obtained using the standard Breit-Wigner parametrization (see 'Note on the Z Boson').

[20] The systematic error is from the uncertainty in the LEP energy calibration.

[21] The error in ADRIANI 93F includes 4 MeV due to the uncertainty in LEP energy calibration.

[22] The error in BUSKULIC 93J includes 4 MeV due to the uncertainty in LEP energy calibration.

[23] ABRAMS 89B uncertainty includes 50 MeV due to the miniSAM background subtraction error.

[24] ALBAJAR 89 result is from a total sample of 33 $Z \rightarrow e^+e^-$ events.

[25] Quoted values of ANSARI 87 are from direct fit. Ratio of Z and W production gives either $\Gamma(Z) < (1.09\pm0.07) \times \Gamma(W)$, CL = 90% or $\Gamma(Z) = (0.82^{+0.19}_{-0.14}\pm0.06) \times \Gamma(W)$. Assuming Standard-Model value $\Gamma(W) = 2.65$ GeV then gives $\Gamma(Z) < 2.89 \pm 0.19$ or $= 2.17^{+0.50}_{-0.37} \pm 0.16$.

Z DECAY MODES

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	e^+e^-			(3.366 ± 0.008) %	
Γ_2	$\mu^+\mu^-$			(3.367 ± 0.013) %	
Γ_3	$\tau^+\tau^-$			(3.360 ± 0.015) %	
Γ_4	$\ell^+\ell^-$		[a]	(3.366 ± 0.006) %	
Γ_5	invisible			$(20.01\ \pm0.16)$ %	
Γ_6	hadrons			$(69.90\ \pm0.15)$ %	
Γ_7	$(u\overline{u}+c\overline{c})/2$			$(10.1\ \pm1.1)$ %	
Γ_8	$(d\overline{d}+s\overline{s}+b\overline{b})/3$			$(16.6\ \pm0.6)$ %	
Γ_9	$c\overline{c}$			$(12.4\ \pm0.6)$ %	
Γ_{10}	$b\overline{b}$			$(15.16\ \pm0.09)$ %	
Γ_{11}	ggg			< 1.1 %	95%
Γ_{12}	$\pi^0\gamma$			$< 5.2 \times 10^{-5}$	95%
Γ_{13}	$\eta\gamma$			$< 5.1 \times 10^{-5}$	95%
Γ_{14}	$\omega\gamma$			$< 6.5 \times 10^{-4}$	95%
Γ_{15}	$\eta'(958)\gamma$			$< 4.2 \times 10^{-5}$	95%
Γ_{16}	$\gamma\gamma$			$< 5.2 \times 10^{-5}$	95%
Γ_{17}	$\gamma\gamma\gamma$			$< 1.0 \times 10^{-5}$	95%
Γ_{18}	$\pi^\pm W^\mp$		[b]	$< 7 \times 10^{-5}$	95%
Γ_{19}	$\rho^\pm W^\mp$		[b]	$< 8.3 \times 10^{-5}$	95%
Γ_{20}	$J/\psi(1S)$X			$(3.66\ \pm0.23) \times 10^{-3}$	
Γ_{21}	$\psi(2S)$X			$(1.60\ \pm0.29) \times 10^{-3}$	
Γ_{22}	$\chi_{c1}(1P)$X			$(2.9\ \pm0.7) \times 10^{-3}$	
Γ_{23}	$\chi_{c2}(1P)$X			$< 3.2 \times 10^{-3}$	90%
Γ_{24}	$\Upsilon(1S)$ X $+\Upsilon(2S)$ X $+\Upsilon(3S)$ X			$(1.0\ \pm0.5) \times 10^{-4}$	
Γ_{25}	$\Upsilon(1S)$X			$< 5.5 \times 10^{-5}$	95%
Γ_{26}	$\Upsilon(2S)$X			$< 1.39 \times 10^{-4}$	95%
Γ_{27}	$\Upsilon(3S)$X			$< 9.4 \times 10^{-5}$	95%
Γ_{28}	$(D^0/\overline{D}^0)$ X			$(20.7\ \pm2.0)$ %	
Γ_{29}	$D^\pm$X			$(12.2\ \pm1.7)$ %	
Γ_{30}	$D^*(2010)^\pm$X		[b]	$(11.4\ \pm1.3)$ %	
Γ_{31}	BX				
Γ_{32}	B^*X				
Γ_{33}	B^0_sX			seen	
Γ_{34}	anomalous $\gamma+$ hadrons		[c]	$< 3.2 \times 10^{-3}$	95%
Γ_{35}	$e^+e^-\gamma$		[c]	$< 5.2 \times 10^{-4}$	95%
Γ_{36}	$\mu^+\mu^-\gamma$		[c]	$< 5.6 \times 10^{-4}$	95%
Γ_{37}	$\tau^+\tau^-\gamma$		[c]	$< 7.3 \times 10^{-4}$	95%
Γ_{38}	$\ell^+\ell^-\gamma\gamma$		[d]	$< 6.8 \times 10^{-6}$	95%
Γ_{39}	$q\overline{q}\gamma\gamma$		[d]	$< 5.5 \times 10^{-6}$	95%
Γ_{40}	$\nu\overline{\nu}\gamma\gamma$		[d]	$< 3.1 \times 10^{-6}$	95%
Γ_{41}	$e^\pm\mu^\mp$	*LF*	[b]	$< 1.7 \times 10^{-6}$	95%
Γ_{42}	$e^\pm\tau^\mp$	*LF*	[b]	$< 9.8 \times 10^{-6}$	95%
Γ_{43}	$\mu^\pm\tau^\mp$	*LF*	[b]	$< 1.2 \times 10^{-5}$	95%

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] The value is for the sum of the charge states of particle/antiparticle states indicated.

[c] See the Particle Listings below for the γ energy range used in this measurement.

[d] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.

Z PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

For the LEP experiments, this parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.82±0.30 OUR FIT				
82.89±1.20±0.89		[26] ABE 95J	SLD	$E^{ee}_{\rm cm}$ = 91.31 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
83.31±0.54	31.4k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.43±0.52	38k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.63±0.53	42k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
84.61±0.49	45.8k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

[26] ABE 95J obtain this measurement from Bhabha events in a restricted fiducial region to improve systematics. They use the values 91.187 and 2.489 GeV for the Z mass and total decay width to extract this partial width.

$\Gamma(\mu^+\mu^-)$ Γ_2

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.83±0.39 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
84.15±0.77	45.6k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.20±0.79	34k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.83±0.65	57k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.62±0.75	46.4k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

$\Gamma(\tau^+\tau^-)$ Γ_3

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.67±0.44 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
83.55±0.91	25k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
84.04±0.94	25k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
82.90±0.77	47k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
84.18±0.79	45.1k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

$\Gamma(\ell^+\ell^-)$ Γ_4

In our fit $\Gamma(\ell^+\ell^-)$ is defined as the partial Z width for the decay into a pair of massless charged leptons. This parameter is not directly used in the 5-parameter fit assuming lepton universality but is derived using the fit results. See the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
83.83±0.27 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
83.56±0.45	102k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.49±0.46	97k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
83.55±0.44	146k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
84.40±0.43	137.3k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

$\Gamma(\text{invisible})$ Γ_5

We use only direct measurements of the invisible partial width to obtain the average value quoted below. The fit value is obtained as a difference between the total and the observed partial widths assuming lepton universality.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
498.3± 4.2 OUR FIT				
517 ±22 OUR AVERAGE				
539 ±26 ±17	410	AKERS 95C	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
450 ±34 ±34	258	BUSKULIC 93L	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
540 ±80 ±40	52	ADEVA 92	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
524 ±40 ±20	172	[27] ADRIANI 92E	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
509.4± 7.0		ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
496.5± 7.9		ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
490.3± 7.3		AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
501 ± 6		BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

[27] ADRIANI 92E improves but does not supersede ADEVA 92, obtained with 1990 data only.

$\Gamma(\text{hadrons})$ Γ_6

This parameter is not directly used in the 5-parameter fit assuming lepton universality, but is derived using the fit results. See the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1740.7± 5.9 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1723 ±10	1.05M	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
1748 ±10	1.09M	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
1741 ±10	1.19M	[28] AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
1746 ±10	1.27M	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

[28] AKERS 94 assumes lepton universality. Without this assumption, it becomes 1742 ± 11 MeV.

Z BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma(e^+e^-)$ Γ_6/Γ_1

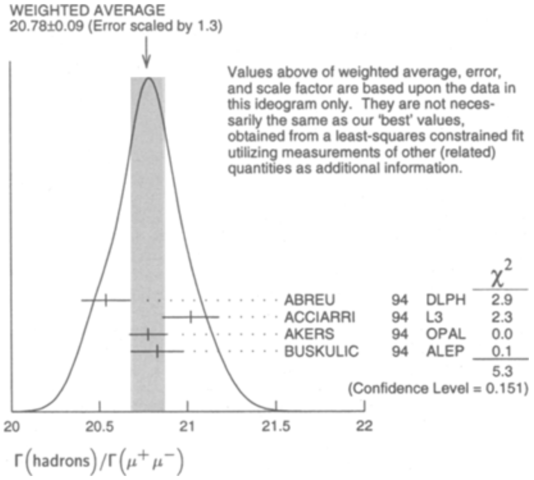
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
20.77± 0.08 OUR FIT				
20.74± 0.18	31.4k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.96± 0.15	38k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.83± 0.16	42k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.59± 0.15	45.8k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.99± 0.25	17k	ACTON 93D	OPAL	Repl. by AKERS 94
20.69± 0.21		BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94
27.0 $^{+11.7}_{-\ 8.8}$	12	[29] ABRAMS 89D	MRK2	$E^{ee}_{\rm cm}$ = 89–93 GeV

[29] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

$\Gamma(\text{hadrons})/\Gamma(\mu^+\mu^-)$ Γ_6/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
20.76±0.07 OUR FIT				
20.78±0.09 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
20.54±0.14	45.6k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
21.02±0.16	34k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.78±0.11	57k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.83±0.15	46.4k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.65±0.17	23k	ACTON 93D	OPAL	Repl. by AKERS 94
20.88±0.20		BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94
18.9 $^{+7.1}_{-5.3}$	13	[30] ABRAMS 89D	MRK2	$E^{ee}_{\rm cm}$ = 89–93 GeV

[30] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.



$\Gamma(\text{hadrons})/\Gamma(\tau^+\tau^-)$ Γ_6/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
20.80±0.08 OUR FIT				
20.81±0.08 OUR AVERAGE				
20.68±0.18	25k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.80±0.20	25k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
21.01±0.15	47k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.70±0.16	45.1k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
21.22±0.25	18k	ACTON 93D	OPAL	Repl. by AKERS 94
20.77±0.23		BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94
15.2 $^{+4.8}_{-3.9}$	21	[31] ABRAMS 89D	MRK2	$E^{ee}_{\rm cm}$ = 89–93 GeV

[31] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

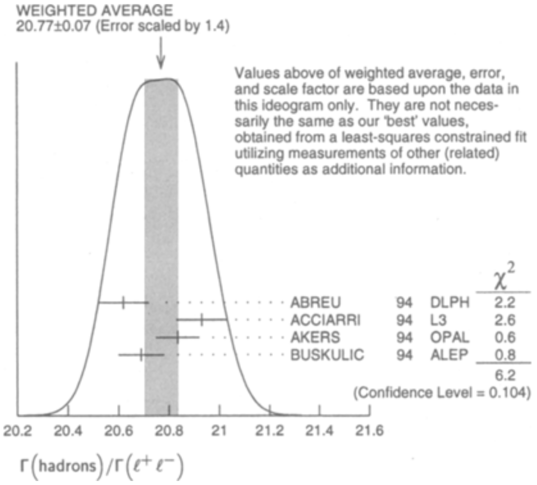
$\Gamma(\text{hadrons})/\Gamma(\ell^+\ell^-)$ Γ_6/Γ_4

ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

Our fit result is obtained requiring lepton universality.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
20.76 ±0.05 OUR FIT				
20.77 ±0.07 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
20.62 ±0.10	102k	ABREU 94	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.93 ±0.10	97k	ACCIARRI 94	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.835±0.086	146k	AKERS 94	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
20.69 ±0.09	137.3k	BUSKULIC 94	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.88 $\pm$0.13	58k	ACTON 93D	OPAL	Repl. by AKERS 94
21.00 $\pm$0.15	40k	ADRIANI 93M	L3	Repl. by ACCIARRI 94
20.78 $\pm$0.13		BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94
18.9 $^{+3.6}_{-3.2}$	46	ABRAMS 89B	MRK2	E^{ee}_{cm}= 89–93 GeV



$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_6/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.6990$\pm$0.0015 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.6983$\pm$0.0023	1.14M	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_1/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03366$\pm$0.00008 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03383$\pm$0.00013	45.8k	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_2/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03367$\pm$0.00013 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03344$\pm$0.00026	46.4k	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\tau^+\tau^-)/\Gamma_{\text{total}}$ Γ_3/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03360$\pm$0.00015 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03366$\pm$0.00028	45.1k	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\ell^+\ell^-)/\Gamma_{\text{total}}$ Γ_4/Γ

ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

Our fit result assumes lepton universality.

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03366$\pm$0.00006 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.03375$\pm$0.00009	137.3k	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\text{invisible})/\Gamma_{\text{total}}$ Γ_5/Γ

See the data, the note, and the fit result for the partial width, Γ_5, above.

VALUE	DOCUMENT ID
0.2001$\pm$0.0016 OUR FIT	

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ Γ_2/Γ_1

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	DOCUMENT ID
1.000$\pm$0.005 OUR FIT	

$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-)$ Γ_3/Γ_1

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	DOCUMENT ID
0.998$\pm$0.005 OUR FIT	

$\Gamma((u\overline{u}+c\overline{c})/2)/\Gamma(\text{hadrons})$ Γ_7/Γ_6

This quantity is the branching ratio of $Z \to$ "up-type" quarks to $Z \to$ hadrons. Except ACKERSTAFF 97T the values of $Z \to$ "up-type" and $Z \to$ "down-type" branchings are extracted from measurements of Γ(hadrons), and $\Gamma(Z \to \gamma+$ jets) where γ is a high-energy (>5 GeV) isolated photon. As the experiments use different procedures and slightly different values of M_Z, Γ(hadrons) and α_s in their extraction procedures, our average has to be taken with caution.

VALUE	DOCUMENT ID	TECN	COMMENT
0.145$\pm$0.015 OUR AVERAGE			
0.160$\pm$0.019$\pm$0.019	[32] ACKERSTAFF 97T	OPAL	E^{ee}_{cm}= 88–94 GeV
0.137$^{+0.038}_{-0.054}$	[33] ABREU 95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.139$\pm$0.026	[34] ACTON 93F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.137$\pm$0.033	[35] ADRIANI 93	L3	E^{ee}_{cm}= 91.2 GeV

[32] ACKERSTAFF 97T measure $\Gamma_{u\overline{u}}/(\Gamma_{d\overline{d}}+\Gamma_{u\overline{u}}+\Gamma_{s\overline{s}}) = 0.258 \pm 0.031 \pm 0.032$. To obtain this branching ratio authors use $R_c+R_b = 0.380 \pm 0.010$. This measurement is fully negatively correlated with the measurement of $\Gamma_{d\overline{d},s\overline{s}}/(\Gamma_{d\overline{d}} + \Gamma_{u\overline{u}} + \Gamma_{s\overline{s}})$ given in the next data block.

[33] ABREU 95X use $M_Z = 91.187 \pm 0.009$ GeV, Γ(hadrons) $= 1725 \pm 12$ MeV and $\alpha_s = 0.123 \pm 0.005$. To obtain this branching ratio we divide their value of $C_{2/3} = 0.91^{+0.25}_{-0.36}$ by their value of $(3C_{1/3} + 2C_{2/3}) = 6.66 \pm 0.05$.

[34] ACTON 93F use the LEP 92 value of Γ(hadrons) $= 1740 \pm 12$ MeV and $\alpha_s = 0.122^{+0.006}_{-0.005}$.

[35] ADRIANI 93 use $M_Z = 91.181 \pm 0.022$ GeV, Γ(hadrons) $= 1742 \pm 19$ MeV and $\alpha_s = 0.125 \pm 0.009$. To obtain this branching ratio we divide their value of $C_{2/3} = 0.92 \pm 0.22$ by their value of $(3C_{1/3} + 2C_{2/3}) = 6.720 \pm 0.076$.

$\Gamma((d\overline{d}+s\overline{s}+b\overline{b})/3)/\Gamma(\text{hadrons})$ Γ_8/Γ_6

This quantity is the branching ratio of $Z \to$ "down-type" quarks to $Z \to$ hadrons. Except ACKERSTAFF 97T the values of $Z \to$ "up-type" and $Z \to$ "down-type" branchings are extracted from measurements of Γ(hadrons), and $\Gamma(Z \to \gamma+$ jets) where γ is a high-energy (>5 GeV) isolated photon. As the experiments use different procedures and slightly different values of M_Z, Γ(hadrons) and α_s in their extraction procedures, our average has to be taken with caution.

VALUE	DOCUMENT ID	TECN	COMMENT
0.237$\pm$0.009 OUR AVERAGE			
0.230$\pm$0.010$\pm$0.010	[36] ACKERSTAFF 97T	OPAL	E^{ee}_{cm}= 88–94 GeV
0.243$^{+0.036}_{-0.026}$	[37] ABREU 95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.241$\pm$0.017	[38] ACTON 93F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.243$\pm$0.022	[39] ADRIANI 93	L3	E^{ee}_{cm}= 91.2 GeV

[36] ACKERSTAFF 97T measure $\Gamma_{d\overline{d},s\overline{s}}/(\Gamma_{d\overline{d}}+\Gamma_{u\overline{u}}+\Gamma_{s\overline{s}}) = 0.371 \pm 0.016 \pm 0.016$. To obtain this branching ratio authors use $R_c+R_b = 0.380 \pm 0.010$. This measurement is fully negatively correlated with the measurement of $\Gamma_{u\overline{u}}/(\Gamma_{d\overline{d}} + \Gamma_{u\overline{u}} + \Gamma_{s\overline{s}})$ presented in the previous data block.

[37] ABREU 95X use $M_Z = 91.187 \pm 0.009$ GeV, Γ(hadrons) $= 1725 \pm 12$ MeV and $\alpha_s = 0.123 \pm 0.005$. To obtain this branching ratio we divide their value of $C_{1/3} = 1.62^{+0.24}_{-0.17}$ by their value of $(3C_{1/3} + 2C_{2/3}) = 6.66 \pm 0.05$.

[38] ACTON 93F use the LEP 92 value of Γ(hadrons) $= 1740 \pm 12$ MeV and $\alpha_s = 0.122^{+0.006}_{-0.005}$.

[39] ADRIANI 93 use $M_Z = 91.181 \pm 0.022$ GeV, Γ(hadrons) $= 1742 \pm 19$ MeV and $\alpha_s = 0.125 \pm 0.009$. To obtain this branching ratio we divide their value of $C_{1/3} = 1.63 \pm 0.15$ by their value of $(3C_{1/3} + 2C_{2/3}) = 6.720 \pm 0.076$.

$R_c = \Gamma(c\overline{c})/\Gamma(\text{hadrons})$ Γ_9/Γ_6

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson." As a cross check we have also performed a weighted average of the R_c measurements taking into account the various common systematic errors. Assuming that the smallest common systematic error is fully correlated, we obtain $R_c = 0.171 \pm 0.009$.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. Combining published and unpublished preliminary LEP and SLD electroweak results (as of end of February 1998) yields $R_c = 0.1734 \pm 0.0048$. The Standard Model predicts $R_c = 0.1723$ for $m_t = 175$ GeV and $M_H = 300$ GeV.

VALUE	DOCUMENT ID	TECN	COMMENT
0.177 $\pm$0.008 OUR FIT			
0.180 $\pm$0.011 $\pm$0.013	[40] ACKERSTAFF 98E	OPAL	E^{ee}_{cm}= 88–94 GeV
0.167 $\pm$0.011 $\pm$0.012	[41] ALEXANDER 96R	OPAL	E^{ee}_{cm}= 88–94 GeV
0.1623$\pm$0.0085$\pm$0.0209	[42] ABREU 95D	DLPH	E^{ee}_{cm}= 88–94 GeV
0.165 $\pm$0.005 $\pm$0.020	[43] BUSKULIC 94G	ALEP	E^{ee}_{cm}= 88–94 GeV
0.187 $\pm$0.031 $\pm$0.023	[44] ABREU 93I	DLPH	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.142 $\pm$0.008 $\pm$0.014	[45] AKERS 95O	OPAL	Repl. by ACKERSTAFF 98E
0.151 $\pm$0.008 $\pm$0.041	[46] ABREU 92O	DLPH	E^{ee}_{cm}= 88–94 GeV

[40] ACKERSTAFF 98E use an inclusive/exclusive double tag. In one jet $D^{*\pm}$ mesons are exclusively reconstruced in several decay channels and in the opposite jet a slow pion

(opposite charge inclusive $D^{*\pm}$) tag is used. The b content of this sample is measured by the simultaneous detection of a lepton in one jet and an inclusively reconstructed $D^{*\pm}$ meson in the opposite jet. The systematic error includes an uncertainty of ±0.006 due to the external branching ratios.

[41] ALEXANDER 96R obtain this value via direct charm counting, summing the partial contributions from D^0, D^+, D_s^+, and Λ_c^+, and assuming that strange-charmed baryons account for the 15% of the Λ_c^+ production. An uncertainty of ±0.005 due to the uncertainties in the charm hadron branching ratios is included in the overall systematics.

[42] ABREU 95D perform a maximum likelihood fit to the combined p and p_T distributions of single and dilepton samples. The second error includes an uncertainty of ±0.0124 due to models and branching ratios.

[43] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.

[44] ABREU 93I assume that the D_s and charmed baryons are equally produced at LEP and CLEO (10 GeV) energies.

[45] AKERS 95O use the presence of a $D^{*\pm}$ to tag $Z \to c\bar{c}$ with $D^* \to D^0\pi$ and $D^0 \to K\pi$. They measure $P_c * \Gamma(c\bar{c})/\Gamma(\text{hadrons})$ to be $(1.006 \pm 0.055 \pm 0.061) \times 10^{-3}$, where P_c is the product branching ratio $B(c \to D^*)B(D^* \to D^0\pi)B(D^0 \to K\pi)$. Assuming that P_c remains unchanged with energy, they use its value $(7.1 \pm 0.5) \times 10^{-3}$ determined at CESR/PETRA to obtain $\Gamma(c\bar{c})/\Gamma(\text{hadrons})$. The second error of AKERS 95O includes an uncertainty of ±0.011 from the uncertainty on P_c.

[46] ABREU 92O use the neural network techinque to tag heavy flavour events among a sample of 123k selected hadronic events. The systematic error consists of three parts: due to Monte Carlo (MC) parametrization (0.023), choice of MC model (0.033) and detector effects (0.009) added in quadrature.

$R_b = \Gamma(b\bar{b})/\Gamma(\text{hadrons})$ Γ_{10}/Γ_6

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson." As a cross check we have also performed a weighted average of the R_b measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. For R_c = 0.177 (as given by OUR FIT above), we obtain $R_b = 0.2169 \pm 0.0012$. For an expected Standard Model value of $R_c = 0.1723$, our weighted average gives $R_b = 0.2172 \pm 0.0012$.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. Combining published and unpublished preliminary LEP and SLD electroweak results (as of end of February 1998) yields $R_b = 0.2170 \pm 0.0009$. The Standard Model predicts $R_b = 0.2158$ for m_t = 175 GeV and M_H = 300 GeV.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.2169±0.0012 OUR FIT				
0.2142±0.0034±0.0015		[47] ABE 98D	SLD	E^{ee}_{cm}= 91.2 GeV
0.2175±0.0014±0.0017		[48] ACKERSTAFF 97K	OPAL	E^{ee}_{cm}= 88–94 GeV
0.2159±0.0009±0.0011		[49] BARATE 97F	ALEP	E^{ee}_{cm}= 88–94 GeV
0.2216±0.0016±0.0021		[50] ABREU 96	DLPH	E^{ee}_{cm}= 88–94 GeV
0.2145±0.0089±0.0067		[51] ABREU 95D	DLPH	E^{ee}_{cm}= 88–94 GeV
0.219 ±0.006 ±0.005		[52] BUSKULIC 94G	ALEP	E^{ee}_{cm}= 88–94 GeV
0.222 ±0.003 ±0.007		[53] ADRIANI 93E	L3	E^{ee}_{cm}= 88–94 GeV
0.222 ±0.011 ±0.007		[54] AKERS 93B	OPAL	E^{ee}_{cm}= 88–94 GeV
0.251 ±0.049 ±0.030	32	[55] JACOBSEN 91	MRK2	E^{ee}_{cm}= 91 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.2167±0.0011±0.0013		[56] BARATE 97E	ALEP	E^{ee}_{cm}= 88–94 GeV
0.229 ±0.011		[57] ABE 96E	SLD	Repl. by ABE 98D
0.2217±0.0020±0.0033		[58] ABREU 95D	DLPH	Repl. by ABREU 96
0.2241±0.0063±0.0046		[59] ABREU 95J	DLPH	Repl. by ABREU 96
0.2171±0.0021±0.0021		[60] AKERS 95B	OPAL	Repl. by ACKERSTAFF 97K
0.228 ±0.005 ±0.005		[61] BUSKULIC 93N	ALEP	E^{ee}_{cm}= 88–94 GeV
$0.222\ ^{+0.033}_{-0.031}\ \pm0.017$		[62] ABREU 92	DLPH	E^{ee}_{cm}= 88–94 GeV
0.219 ±0.014 ±0.019		[63] ABREU 92K	DLPH	E^{ee}_{cm}= 88–94 GeV
0.232 ±0.005 ±0.017		[64] ABREU 92O	DLPH	E^{ee}_{cm}= 88–94 GeV
$0.23\ ^{+0.10}_{-0.08}\ ^{+0.05}_{-0.04}$	15	[65] KRAL 90	MRK2	E^{ee}_{cm}= 89–93 GeV

[47] ABE 98D use a double tag based on 3D impact parameter with reconstruction of secondary vertices. The charm background is reduced by requiring the invariant mass at the secondary vertex to be above 2 GeV. The systematic error includes an uncertainty of ±0.0002 due to the uncertainty on R_c.

[48] ACKERSTAFF 97K use lepton and/or separated decay vertex to tag independently each hemisphere. Comparing the numbers of single- and double-tagged events, they determine the b-tagging efficiency directly from the data.

[49] BARATE 97F combine the lifetime-mass hemisphere tag (BARATE 97E) with event shape information and lepton tag to identify $Z \to b\bar{b}$ candidates. They further use c- and uds-selection tags to identify the background. For R_c different from its Standard Model value of 0.172, R_b varies as $-0.019 \times (R_c - 0.172)$.

[50] ABREU 96 obtain this result combining several analyses (double lifetime tag, mixed tag and multivariate analysis). This value is obtained assuming $R_c = \Gamma(c\bar{c})/\Gamma(\text{hadrons}) = 0.172$. For a value of R_c different from this by an amount ΔR_c the change in the value is given by $-0.087 \cdot \Delta R_c$.

[51] ABREU 95D perform a maximum likelihood fit to the combined p and p_T distributions of single and dilepton samples. The second error includes an uncertainty of ±0.0023 due to models and branching ratios.

[52] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.

[53] ADRIANI 93E use a multidimensional analysis based on a neural network approach.

[54] AKERS 93B use a simultaneous fit to single and dilepton events (electrons and muons) to tag $Z \to b\bar{b}$.

[55] JACOBSEN 91 tagged $b\bar{b}$ events by requiring coincidence of ≥ 3 tracks with significant impact parameters using vertex detector. Systematic error includes lifetime and decay uncertainties (±0.014).

[56] BARATE 97E combine a lifetime tag with a mass cut based on the mass difference between c hadrons and b hadrons.

[57] ABE 96E obtain this value by combining results from three different b-tagging methods (2D impact parameter, 3D impact parameter, and 3D displaced vertex).

[58] ABREU 95D obtain this result combining several analyses (double-lifetime tag and mixed tags). The second error contains an uncertainty of ±0.0029 due to the total systematics and an uncertainty of ±0.0016 due to an 8% variation of $\Gamma(c\bar{c})/\Gamma(\text{hadrons})$ around its Standard Model value (0.171 ± 0.014). Combining with their own lepton analysis, ABREU 95D obtain 0.2210 ± 0.0033 ± 0.0003 (models) ±0.0014 $[\Gamma(c\bar{c})/\Gamma(\text{hadrons})]$.

[59] ABREU 95J obtain this value with a multivariate analysis based on event shape and particle trajectories near the interaction point. The second error contains an uncertainty of ±0.0012 due to an 8% variation of $\Gamma(c\bar{c})/\Gamma(\text{hadrons})$ around its Standard Model value (0.171 ± 0.014).

[60] AKERS 95B select events based on the lepton and/or vertex tag independently in each hemisphere. Comparing the numbers of single- and double-tagged events, they determine the b-tagging efficiency directly from data.

[61] BUSKULIC 93N use event shape and high p_T lepton discriminators applied to both hemispheres.

[62] ABREU 92 result is from an indirect technique. They measure the lifetime τ_B, but use a world average of τ_B independent of $\Gamma(b\bar{b})$ and compare to their $\Gamma(b\bar{b})$ dependent lifetime from a hadron sample.

[63] ABREU 92K use boosted−sphericity technique to tag and enrich the b-$\bar{b}$ content with a sample of 50k hadronic events. Most of the systematic error is from hadronization uncertainty.

[64] ABREU 92O use the neural network technique to tag heavy flavour events among a sample of 123k selected hadronic events. The systematic error consists of three parts: due to Monte Carlo (MC) parametrization (0.010), choice of MC model (0.008), and detector effécts (0.011) added in quadrature.

[65] KRAL 90 used isolated leptons and found $\Gamma(b\bar{b})/\Gamma(\text{total}) = 0.17^{+0.07}_{-0.06}{}^{+0.04}_{-0.03}$.

$\Gamma(ggg)/\Gamma(\text{hadrons})$ Γ_{11}/Γ_6

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.6 \times 10^{-2}$	95	[66] ABREU 96S	DLPH	E^{ee}_{cm}= 88–94 GeV

[66] This branching ratio is slightly dependent on the jet-finder algorithm. The value we quote is obtained using the JADE algorithm, while using the DURHAM algorithm ABREU 96S obtain an upper limit of 1.5×10^{-2}.

$\Gamma(\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.2 \times 10^{-5}$	95	[67] ACCIARRI 95G	L3	E^{ee}_{cm}= 88–94 GeV
$<5.5 \times 10^{-5}$	95	ABREU 94B	DLPH	E^{ee}_{cm}= 88–94 GeV
$<2.1 \times 10^{-4}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$<1.4 \times 10^{-4}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.2 \times 10^{-4}$	95	[68] ADRIANI 92B	L3	Repl. by ACCIARRI 95G

[67] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ACCIARRI 95G.

[68] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ADRIANI 92B.

$\Gamma(\eta\gamma)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.6 \times 10^{-5}$	95	ACCIARRI 95G	L3	E^{ee}_{cm}= 88–94 GeV
$<8.0 \times 10^{-5}$	95	ABREU 94B	DLPH	E^{ee}_{cm}= 88–94 GeV
$<5.1 \times 10^{-5}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV
$<2.0 \times 10^{-4}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.8 \times 10^{-4}$	95	ADRIANI 92B	L3	Repl. by ACCIARRI 95G

$\Gamma(\omega\gamma)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.5 \times 10^{-4}$	95	ABREU 94B	DLPH	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\eta'(958)\gamma)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.2 \times 10^{-5}$	95	DECAMP 92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{16}/Γ

This decay would violate the Landau-Yang theorem.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.2 \times 10^{-5}$	95	[69] ACCIARRI 95G	L3	E^{ee}_{cm}= 88–94 GeV
$<5.5 \times 10^{-5}$	95	ABREU 94B	DLPH	E^{ee}_{cm}= 88–94 GeV
$<1.4 \times 10^{-4}$	95	AKRAWY 91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.2 \times 10^{-4}$	95	[70] ADRIANI 92B	L3	Repl. by ACCIARRI 95G

[69] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ACCIARRI 95G.

[70] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ADRIANI 92B.

$\Gamma(\gamma\gamma\gamma)/\Gamma_{\rm total}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-5}$	95	[71] ACCIARRI 95C	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
$<1.7 \times 10^{-5}$	95	[71] ABREU 94B	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
$<6.6 \times 10^{-5}$	95	AKRAWY 91F	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.3 \times 10^{-5}$	95	ADRIANI 92B	L3	Repl. by ACCIARRI 95C

[71] Limit derived in the context of composite Z model.

$\Gamma(\pi^{\pm} W^{\mp})/\Gamma_{\rm total}$ — Γ_{18}/Γ

The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7 \times 10^{-5}$	95	DECAMP 92	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

$\Gamma(\rho^{\pm} W^{\mp})/\Gamma_{\rm total}$ — Γ_{19}/Γ

The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.3 \times 10^{-5}$	95	DECAMP 92	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

$\Gamma(J/\psi(1S)X)/\Gamma_{\rm total}$ — Γ_{20}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.66±0.23 OUR AVERAGE				
3.40±0.23±0.27	441	[72] ACCIARRI 97J	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
3.9 ±0.2 ±0.3	511	[73] ALEXANDER 96B	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
3.73±0.39±0.36	153	[74] ABREU 94P	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.6 ±0.5 ±0.4	121	[74] ADRIANI 93J	L3	Repl. by ACCIARRI 97J

[72] ACCIARRI 97J combine $\mu^+\mu^-$ and e^+e^- $J/\psi(1S)$ decay channels and take into account the common systematic error.

[73] ALEXANDER 96B identify $J/\psi(1S)$ from the decays into lepton pairs. (4.8 ± 2.4)% of this branching ratio is due to prompt $J/\psi(1S)$ production (ALEXANDER 96N).

[74] Combining $\mu^+\mu^-$ and e^+e^- channels and taking into account the common systematic errors. $(7.7^{+6.3}_{-5.4})$% of this branching ratio is due to prompt $J/\psi(1S)$ production.

$\Gamma(\psi(2S)X)/\Gamma_{\rm total}$ — Γ_{21}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.60±0.29 OUR AVERAGE				
1.6 ±0.5 ±0.3	39	[75] ACCIARRI 97J	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
1.6 ±0.3 ±0.2	46.9	[76] ALEXANDER 96B	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
1.60±0.73±0.33	5.4	[77] ABREU 94P	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV

[75] ACCIARRI 97J measure this branching ratio via the decay channel $\psi(2S) \rightarrow \ell^+\ell^-$ ($\ell = \mu, e$).

[76] ALEXANDER 96B measure this branching ratio via the decay channel $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$, with $J/\psi \rightarrow \ell^+\ell^-$.

[77] ABREU 94P measure this branching ratio via decay channel $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$, with $J/\psi \rightarrow \mu^+\mu^-$.

$\Gamma(\chi_{c1}(1P)X)/\Gamma_{\rm total}$ — Γ_{22}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.9±0.7 OUR AVERAGE				
2.7±0.6±0.5	33	[78] ACCIARRI 97J	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV
$5.0\pm2.1^{+1.5}_{-0.9}$	6.4	[79] ABREU 94P	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.5±2.9±0.6	19	[79] ADRIANI 93J	L3	Repl. by ACCIARRI 97J

[78] ACCIARRI 97J measure this branching ratio via the decay channel $\chi_{c1} \rightarrow J/\psi + \gamma$, with $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = \mu, e$). The $M(\ell^+\ell^-\gamma)$–$M(\ell^+\ell^-)$ mass difference spectrum is fitted with two gaussian shapes for χ_{c1} and χ_{c2}.

[79] This branching ratio is measured via the decay channel $\chi_{c1} \rightarrow J/\psi + \gamma$, with $J/\psi \rightarrow \mu^+\mu^-$.

$\Gamma(\chi_{c2}(1P)X)/\Gamma_{\rm total}$ — Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.2 \times 10^{-3}$	90	[80] ACCIARRI 97J	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV

[80] ACCIARRI 97J derive this limit via the decay channel $\chi_{c2} \rightarrow J/\psi + \gamma$, with $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = \mu, e$). The $M(\ell^+\ell^-\gamma)$–$M(\ell^+\ell^-)$ mass difference spectrum is fitted with two gaussian shapes for χ_{c1} and χ_{c2}.

$\Gamma(\Upsilon(1S)X + \Upsilon(2S)X + \Upsilon(3S)X)/\Gamma_{\rm total}$ — $\Gamma_{24}/\Gamma = (\Gamma_{25}+\Gamma_{26}+\Gamma_{27})/\Gamma$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
1.0±0.4±0.22	6.4	[81] ALEXANDER 96F	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV

[81] ALEXANDER 96F identify the Υ (which refers to any of the three lowest bound states) through its decay into e^+e^- and $\mu^+\mu^-$. The systematic error includes an uncertainty of ±0.2 due to the production mechanism.

$\Gamma(\Upsilon(1S)X)/\Gamma_{\rm total}$ — Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.5 \times 10^{-5}$	95	[82] ACCIARRI 97R	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV

[82] ACCIARRI 97R search for $\Upsilon(1S)$ through its decay into $\ell^+\ell^-$ (ℓ = e or μ).

$\Gamma(\Upsilon(2S)X)/\Gamma_{\rm total}$ — Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<13.9 \times 10^{-5}$	95	[83] ACCIARRI 97R	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV

[83] ACCIARRI 97R search for $\Upsilon(2S)$ through its decay into $\ell^+\ell^-$ (ℓ = e or μ).

$\Gamma(\Upsilon(3S)X)/\Gamma_{\rm total}$ — Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.4 \times 10^{-5}$	95	[84] ACCIARRI 97R	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV

[84] ACCIARRI 97R search for $\Upsilon(3S)$ through its decay into $\ell^+\ell^-$ (ℓ = e or μ).

$\Gamma((D^0/\overline{D}^0)X)/\Gamma(\text{hadrons})$ — Γ_{28}/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.296±0.019±0.021	369	[85] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV

[85] The $(D^0/\overline{D}^0)$ states in ABREU 93I are detected by the $K\pi$ decay mode. This is a corrected result (see the erratum of ABREU 93I).

$\Gamma(D^{\pm}X)/\Gamma(\text{hadrons})$ — Γ_{29}/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.174±0.016±0.018	539	[86] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV

[86] The $D^{\pm}$ states in ABREU 93I are detected by the $K\pi\pi$ decay mode. This is a corrected result (see the erratum of ABREU 93I).

$\Gamma(D^*(2010)^{\pm}X)/\Gamma(\text{hadrons})$ — Γ_{30}/Γ_6

The value is for the sum of the charge states indicated.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.163±0.019 OUR AVERAGE		Error includes scale factor of 1.3.		
0.155±0.010±0.013	358	[87] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
0.21 ±0.04	362	[88] DECAMP 91J	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

[87] $D^*(2010)^{\pm}$ in ABREU 93I are reconstructed from $D^0\pi^{\pm}$, with $D^0 \rightarrow K^-\pi^+$. The new CLEO II measurement of B($D^{*\pm} \rightarrow D^0\pi^{\pm}$) = (68.1 ± 1.6) % is used. This is a corrected result (see the erratum of ABREU 93I).

[88] DECAMP 91J report B($D^*(2010)^+ \rightarrow D^0\pi^+$) B($D^0 \rightarrow K^-\pi^+$) $\Gamma(D^*(2010)^{\pm}X)$ / Γ(hadrons) = (5.11 ± 0.34) × 10^{-3}. They obtained the above number assuming B($D^0 \rightarrow K^-\pi^+$) = (3.62±0.34±0.44)% and B($D^*(2010)^+ \rightarrow D^0\pi^+$) = (55±4)%. We have rescaled their original result of 0.26 ± 0.05 taking into account the new CLEO II branching ratio B($D^*(2010)^+ \rightarrow D^0\pi^+$) = (68.1 ± 1.6)%.

$\Gamma(B^0_sX)/\Gamma(\text{hadrons})$ — Γ_{33}/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
seen	[89] ABREU 92M	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
seen	[90] ACTON 92N	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
seen	[91] BUSKULIC 92E	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV

[89] ABREU 92M reported value is $\Gamma(B^0_sX)$∗B($B^0_s \rightarrow D_s\mu\nu_\mu X$) ∗B($D_s \rightarrow \phi\pi$)/Γ(hadrons) = (18 ± 8) × 10^{-5}.

[90] ACTON 92N find evidence for B^0_s production using D_s-ℓ correlations, with $D^+_s \rightarrow \phi\pi^+$ and $K^*(892)K^+$. Assuming R_b from the Standard Model and averaging over the e and μ channels, authors measure the product branching fraction to be $f(\overline{b} \rightarrow B^0_s)$×B($B^0_s \rightarrow D^-_s\ell^+\nu_\ell X$)×B($D^-_s \rightarrow \phi\pi^-$) = (3.9 ± 1.1 ± 0.8) × 10^{-4}.

[91] BUSKULIC 92E find evidence for B^0_s production using D_s-ℓ correlations, with $D^+_s \rightarrow \phi\pi^+$ and $K^*(892)K^+$. Using B($D^+_s \rightarrow \phi\pi^+$) = (2.7 ± 0.7)% and summing up the e and μ channels, the weighted average product branching fraction is measured to be B($\overline{b} \rightarrow B^0_s$)×B($B^0_s \rightarrow D^-_s\ell^+\nu_\ell X$) = $0.040 \pm 0.011^{+0.010}_{-0.012}$.

$\Gamma(B^*X)/[\Gamma(BX)+\Gamma(B^*X)]$ — $\Gamma_{32}/(\Gamma_{31}+\Gamma_{32})$

As the experiments assume different values of the b-baryon contribution, our average should be taken with caution. If we assume a common baryon production fraction f_{Λ_b} = (13.2 ± 4.1)% as given in the 1996 edition of this *Review* OUR AVERAGE becomes 0.77 ± 0.04.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.75 ±0.04 OUR AVERAGE				
0.760±0.036±0.083		[92] ACKERSTAFF 97M	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV
0.771±0.026±0.070		[93] BUSKULIC 96D	ALEP	$E^{ee}_{\rm cm}$ = 88–94 GeV
0.72 ±0.03 ±0.06		[94] ABREU 95R	DLPH	$E^{ee}_{\rm cm}$ = 88–94 GeV
0.76 ±0.08 ±0.06	1378	[95] ACCIARRI 95B	L3	$E^{ee}_{\rm cm}$ = 88–94 GeV

[92] ACKERSTAFF 97M use an inclusive B reconstruction method and assume a (13.2 ± 4.1)% b-baryon contribution. The value refers to a b-flavored meson mixture of B_u, B_d, and B_s.

[93] BUSKULIC 96D use an inclusive reconstruction of B hadrons and assume a (12.2 ± 4.3)% b-baryon contribution. The value refers to a b-flavored mixture of B_u, B_d, and B_s.

[94] ABREU 95R use an inclusive B-reconstruction method and assume a (10 ± 4)% b-baryon contribution. The value refers to a b-flavored meson mixture of B_u, B_d, and B_s.

[95] ACCIARRI 95B assume a 9.4% b-baryon contribution. The value refers to a b-flavored mixture of B_u, B_d, and B_s.

$\Gamma(\text{anomalous } \gamma + \text{hadrons})/\Gamma_{\rm total}$ — Γ_{34}/Γ

Limits on additional sources of prompt photons beyond expectations for final-state bremsstrahlung.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.2 \times 10^{-3}$	95	[96] AKRAWY 90J	OPAL	$E^{ee}_{\rm cm}$ = 88–94 GeV

[96] AKRAWY 90J report Γ(γX) < 8.2 MeV at 95%CL. They assume a three-body $\gamma q\overline{q}$ distribution and use E(γ) > 10 GeV.

$\Gamma(e^+e^-\gamma)/\Gamma_{\rm total}$ Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.2 \times 10^{-4}}$	95	[97] ACTON 91B	OPAL	$E_{\rm cm}^{ee}$= 91.2 GeV

[97] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (> 0.9 GeV).

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\rm total}$ Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.6 \times 10^{-4}}$	95	[98] ACTON 91B	OPAL	$E_{\rm cm}^{ee}$= 91.2 GeV

[98] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (> 0.9 GeV).

$\Gamma(\tau^+\tau^-\gamma)/\Gamma_{\rm total}$ Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<7.3 \times 10^{-4}}$	95	[99] ACTON 91B	OPAL	$E_{\rm cm}^{ee}$= 91.2 GeV

[99] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy (> 0.9 GeV).

$\Gamma(\ell^+\ell^-\gamma\gamma)/\Gamma_{\rm total}$ Γ_{38}/Γ

The value is the sum over $\ell = e, \mu, \tau$.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<6.8 \times 10^{-6}}$	95	[100] ACTON 93E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

[100] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(q\overline{q}\gamma\gamma)/\Gamma_{\rm total}$ Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<5.5 \times 10^{-6}}$	95	[101] ACTON 93E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

[101] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(\nu\overline{\nu}\gamma\gamma)/\Gamma_{\rm total}$ Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<3.1 \times 10^{-6}}$	95	[102] ACTON 93E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

[102] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(e^\pm\mu^\mp)/\Gamma(e^+e^-)$ Γ_{41}/Γ_1

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<0.07}$	90	ALBAJAR 89	UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\rm total}$ Γ_{41}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.5 \times 10^{-6}$	95	ABREU 97C	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
$\mathbf{<1.7 \times 10^{-6}}$	95	AKERS 95W	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$<0.6 \times 10^{-5}$	95	ADRIANI 93I	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$<2.6 \times 10^{-5}$	95	DECAMP 92	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV

$\Gamma(e^\pm\tau^\mp)/\Gamma_{\rm total}$ Γ_{42}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.2 \times 10^{-5}$	95	ABREU 97C	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
$\mathbf{<9.8 \times 10^{-6}}$	95	AKERS 95W	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$<1.3 \times 10^{-5}$	95	ADRIANI 93I	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$<1.2 \times 10^{-4}$	95	DECAMP 92	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV

$\Gamma(\mu^\pm\tau^\mp)/\Gamma_{\rm total}$ Γ_{43}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{<1.2 \times 10^{-5}}$	95	ABREU 97C	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
$<1.7 \times 10^{-5}$	95	AKERS 95W	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$<1.9 \times 10^{-5}$	95	ADRIANI 93I	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$<1.0 \times 10^{-4}$	95	DECAMP 92	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV

AVERAGE PARTICLE MULTIPLICITIES IN HADRONIC Z DECAY

Summed over particle and antiparticle, when appropriate.

$\langle N_{\pi^\pm}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
17.05±0.43	AKERS 94P	OPAL	$E_{\rm cm}^{ee}$= 91.2 GeV

$\langle N_{\pi^0}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
9.79±0.28 OUR AVERAGE			
9.63±0.13±0.63	BARATE 97J	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV
9.90±0.02±0.33	ACCIARRI 96	L3	$E_{\rm cm}^{ee}$= 91.2 GeV
9.2 ±0.2 ±1.0	ADAM 96	DLPH	$E_{\rm cm}^{ee}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
9.18±0.03±0.73	ACCIARRI 94B	L3	Repl. by ACCIARRI 96

$\langle N_\eta\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.93 ±0.01 ±0.09	ACCIARRI 96	L3	$E_{\rm cm}^{ee}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.91 ±0.02 ±0.11	ACCIARRI 94B	L3	Repl. by ACCIARRI 96
0.298±0.023±0.021	[103] BUSKULIC 92D	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV

[103] BUSKULIC 92D obtain this value for $x> 0.1$.

$\langle N_\rho\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
1.30±0.12 OUR AVERAGE			
1.45±0.06±0.20	BUSKULIC 96H	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV
1.21±0.04±0.15	ABREU 95L	DLPH	$E_{\rm cm}^{ee}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.43±0.12±0.22	ABREU 93	DLPH	Repl. by ABREU 95L

$\langle N_\omega\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
1.11±0.11 OUR AVERAGE			
1.17±0.09±0.15	ACCIARRI 97D	L3	$E_{\rm cm}^{ee}$= 91.2 GeV
1.07±0.06±0.13	BUSKULIC 96H	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV

$\langle N_{\eta'}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.25 ±0.04	[104] ACCIARRI 97D	L3	$E_{\rm cm}^{ee}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.068±0.018±0.016	[105] BUSKULIC 92D	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV

[104] ACCIARRI 97D obtain this value averaging over the two decay channels $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \rho^0\gamma$.

[105] BUSKULIC 92D obtain this value for $x> 0.1$.

$\langle N_{f_0(980)}\rangle$

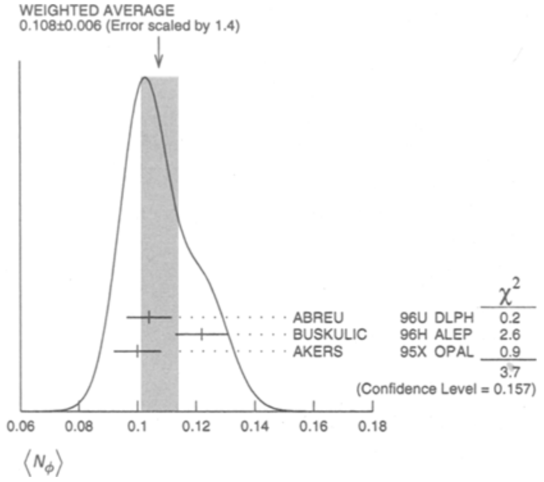
VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.098±0.016	[106] ABREU 95L	DLPH	$E_{\rm cm}^{ee}$= 91.2 GeV
0.10 ±0.03 ±0.019	[107] ABREU 93	DLPH	Repl. by ABREU 95L

[106] ABREU 95L obtain this value for $0.05 <x< 0.6$.

[107] ABREU 93 obtain this value for $x> 0.05$.

$\langle N_\phi\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.108±0.006 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.		
0.104±0.003±0.007	ABREU 96U	DLPH	$E_{\rm cm}^{ee}$= 91.2 GeV
0.122±0.004±0.008	BUSKULIC 96H	ALEP	$E_{\rm cm}^{ee}$= 91.2 GeV
0.100±0.004±0.007	AKERS 95X	OPAL	$E_{\rm cm}^{ee}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.086±0.015±0.010	ACTON 92O	OPAL	Repl. by AKERS 95X



$\langle N_{f_2(1270)}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.170±0.043	[108] ABREU 95L	DLPH	$E_{\rm cm}^{ee}$= 91.2 GeV
0.11 ±0.04 ±0.03	[109] ABREU 93	DLPH	Repl. by ABREU 95L

[108] ABREU 95L obtain this value for $x> 0.05$.

[109] ABREU 93 obtain this value for $x> 0.1$.

$\langle N_{f'_2(1525)} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.020±0.005±0.006	ABREU 96C	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{K^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
2.37±0.11 OUR AVERAGE			
2.26±0.01±0.18	ABREU 95F	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
2.42±0.13	AKERS 94P	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{K^0} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
2.013±0.023 OUR AVERAGE			
2.024±0.006±0.042	ACCIARRI 97L	L3	$E^{ee}_{\rm cm}$= 91.2 GeV
1.962±0.022±0.056	ABREU 95L	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
1.99 ±0.01 ±0.04	AKERS 95U	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
2.061±0.047	BUSKULIC 94K	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.04 ±0.02 ±0.14	ACCIARRI 94B	L3	Repl. by ACCIARRI 97L
2.12 ±0.05 ±0.04	ABREU 92G	DLPH	Repl. by ABREU 95L

$\langle N_{K^*(892)^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.72 ±0.05 OUR AVERAGE			
0.712±0.031±0.059	ABREU 95L	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
0.72 ±0.02 ±0.08	ACTON 93	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.33 ±0.11 ±0.24	ABREU 92G	DLPH	Repl. by ABREU 95L

$\langle N_{K^*(892)^0} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.752±0.025 OUR AVERAGE			
0.74 ±0.02 ±0.02	ACKERSTAFF 97S	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
0.77 ±0.02 ±0.07	ABREU 96U	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
0.83 ±0.01 ±0.09	BUSKULIC 96H	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
0.97 ±0.18 ±0.31	ABREU 93	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.74 ±0.03 ±0.03	AKERS 95X	OPAL	Repl. by ACKERSTAFF 97S

$\langle N_{K^*_2(1430)} \rangle$

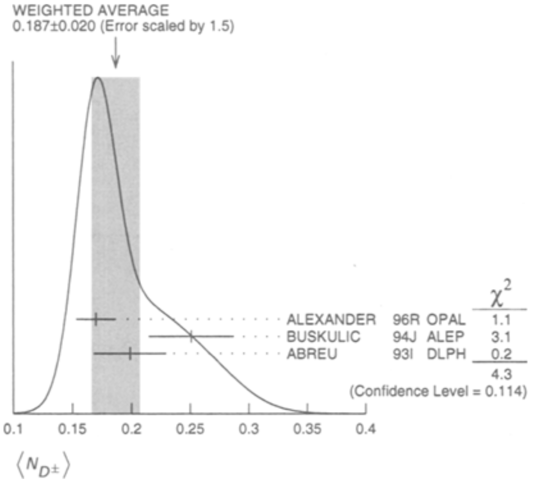
VALUE	DOCUMENT ID	TECN	COMMENT
0.079±0.026±0.031	ABREU 96U	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.19 ±0.04 ±0.06	[110] AKERS 95X	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

[110] AKERS 95X obtain this value for $x < 0.3$.

$\langle N_{D^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.187±0.020 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.		
0.170±0.009±0.014	ALEXANDER 96R	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
0.251±0.026±0.025	BUSKULIC 94J	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
0.199±0.019±0.024	[111] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV

[111] See ABREU 95 (erratum).



$\langle N_{D^0} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.462±0.026 OUR AVERAGE			
0.465±0.017±0.027	ALEXANDER 96R	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
0.518±0.052±0.035	BUSKULIC 94J	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
0.403±0.038±0.044	[112] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV

[112] See ABREU 95 (erratum).

$\langle N_{D_s^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.131±0.010±0.018	ALEXANDER 96R	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{D^*(2010)^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.183 ±0.008 OUR AVERAGE			
0.1854±0.0041±0.0091	[113] ACKERSTAFF 98E	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
0.187 ±0.015 ±0.013	BUSKULIC 94J	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
0.171 ±0.012 ±0.016	[114] ABREU 93I	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.183 ±0.009 ±0.011	[115] AKERS 95O	OPAL	Repl. by ACKERSTAFF 98E

[113] ACKERSTAFF 98E systematic error includes an uncertainty of ±0.0069 due to the branching ratios $B(D^{*+} \to D^0\pi^+) = 0.683 \pm 0.014$ and $B(D^0 \to K^-\pi^+) = 0.0383 \pm 0.0012$.

[114] See ABREU 95 (erratum).

[115] AKERS 95O systematic error includes an uncertainty of ±0.008 due to the $D^{*\pm}$ and D^0 branching ratios [they use $B(D^* \to D^0\pi) = 0.681 \pm 0.016$ and $B(D^0 \to K\pi) = 0.0401 \pm 0.0014$ to obtain this measurement].

$\langle N_{D_{s1}(2536)^+} \rangle$

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$2.9^{+0.7}_{-0.6}\pm0.2$	[116] ACKERSTAFF 97W	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

[116] ACKERSTAFF 97W obtain this value for $x > 0.6$ and with the assumption that its decay width is saturated by the $D^* K$ final states.

$\langle N_{B^*} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.28 ±0.01 ±0.03	[117] ABREU 95R	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV

[117] ABREU 95R quote this value for a flavor-averaged excited state.

$\langle N_{J/\psi(1S)} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0056±0.0003±0.0004	[118] ALEXANDER 96B	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

[118] ALEXANDER 96B identify $J/\psi(1S)$ from the decays into lepton pairs.

$\langle N_{\psi(2S)} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0023±0.0004±0.0003	ALEXANDER 96B	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_p \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.98±0.09 OUR AVERAGE			
1.07±0.01±0.14	ABREU 95F	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
0.92±0.11	AKERS 94P	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{\Delta(1232)^{++}} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.087±0.033 OUR AVERAGE	Error includes scale factor of 2.4.		
0.079±0.009±0.011	ABREU 95W	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
0.22 ±0.04 ±0.04	ALEXANDER 95D	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_\Lambda \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.372±0.007 OUR AVERAGE			
0.364±0.004±0.017	ACCIARRI 97L	L3	$E^{ee}_{\rm cm}$= 91.2 GeV
0.374±0.002±0.010	ALEXANDER 97D	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV
0.386±0.016	BUSKULIC 94K	ALEP	$E^{ee}_{\rm cm}$= 91.2 GeV
0.357±0.003±0.017	ABREU 93L	DLPH	$E^{ee}_{\rm cm}$= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.37 ±0.01 ±0.04	ACCIARRI 94B	L3	Repl. by ACCIARRI 97L
0.351±0.019	ACTON 92J	OPAL	Repl. by ALEXANDER 97D

$\langle N_{\Lambda(1520)} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0213±0.0021±0.0019	ALEXANDER 97D	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{\Sigma^+} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.099±0.008±0.013	ALEXANDER 97E	OPAL	$E^{ee}_{\rm cm}$= 91.2 GeV

$\langle N_{\Sigma^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.083±0.006±0.009	ALEXANDER 97E	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma^+ + \Sigma^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.181±0.018 OUR AVERAGE			
0.182±0.010±0.016	[119] ALEXANDER 97E	OPAL	E^{ee}_{cm}= 91.2 GeV
0.170±0.014±0.061	ABREU 95O	DLPH	E^{ee}_{cm}= 91.2 GeV

[119] We have combined the values of $\langle N_{\Sigma^+}\rangle$ and $\langle N_{\Sigma^-}\rangle$ from ALEXANDER 97E adding the statistical and systematic errors of the two final states separately in quadrature. If isospin symmetry is assumed this value becomes 0.174 ± 0.010 ± 0.015.

$\langle N_{\Sigma^0}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.070±0.011 OUR AVERAGE			
0.071±0.012±0.013	ALEXANDER 97E	OPAL	E^{ee}_{cm}= 91.2 GeV
0.070±0.010±0.010	ADAM 96B	DLPH	E^{ee}_{cm}= 91.2 GeV

$\langle N_{(\Sigma^+ + \Sigma^- + \Sigma^0)/3}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.084±0.005±0.008	ALEXANDER 97E	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma(1385)^+}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0239±0.0009±0.0012	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma(1385)^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0240±0.0010±0.0014	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma(1385)^+ + \Sigma(1385)^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.046 ±0.004 OUR AVERAGE	Error includes scale factor of 1.6.		
0.0479±0.0013±0.0026	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV
0.0382±0.0028±0.0045	ABREU 95O	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0380±0.0062	ACTON 92J	OPAL	Repl. by ALEXANDER 97D

$\langle N_{\Xi^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0258±0.0009 OUR AVERAGE			
0.0259±0.0004±0.0009	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV
0.0250±0.0009±0.0021	ABREU 95O	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.020 ±0.004 ±0.003	ABREU 92G	DLPH	Repl. by ABREU 95O
0.0206±0.0021	ACTON 92J	OPAL	Repl. by ALEXANDER 97D

$\langle N_{\Xi(1530)^0}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0053±0.0013 OUR AVERAGE	Error includes scale factor of 3.2.		
0.0068±0.0005±0.0004	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV
0.0041±0.0004±0.0004	ABREU 95O	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0063±0.0014	ACTON 92J	OPAL	Repl. by ALEXANDER 97D

$\langle N_{\Omega^-}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.00164±0.00028 OUR AVERAGE			
0.0018 ±0.0003 ±0.0002	ALEXANDER 97D	OPAL	E^{ee}_{cm}= 91.2 GeV
0.0014 ±0.0002 ±0.0004	ADAM 96B	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0050 ±0.0015	ACTON 92J	OPAL	Repl. by ALEXANDER 97D

$\langle N_{\Lambda_c^+}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
0.078±0.012±0.012	ALEXANDER 96R	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{charged}\rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
21.00±0.13 OUR AVERAGE			
21.05±0.20	AKERS 95Z	OPAL	E^{ee}_{cm}= 91.2 GeV
20.91±0.03±0.22	BUSKULIC 95R	ALEP	E^{ee}_{cm}= 91.2 GeV
21.40±0.43	ACTON 92B	OPAL	E^{ee}_{cm}= 91.2 GeV
20.71±0.04±0.77	ABREU 91H	DLPH	E^{ee}_{cm}= 91.2 GeV
20.7 ±0.7	ADEVA 91I	L3	E^{ee}_{cm}= 91.2 GeV
20.1 ±1.0 ±0.9	ABRAMS 90	MRK2	E^{ee}_{cm}= 91.1 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
20.85±0.02±0.24	DECAMP 91K	ALEP	Repl. by BUSKULIC 95R

Z HADRONIC POLE CROSS SECTION

This quantity is defined as

$$\sigma^0_h = \frac{12\pi}{M^2_Z} \frac{\Gamma(e^+e^-)\,\Gamma(\text{hadrons})}{\Gamma^2_Z}$$

It is one of the parameters used in the Z lineshape fit. (See the 'Note on the Z Boson.')

VALUE (nb)	EVTS	DOCUMENT ID	TECN	COMMENT
41.54±0.14 OUR FIT				
41.49±0.10 OUR AVERAGE				
41.23±0.20	1.05M	ABREU 94	DLPH	E^{ee}_{cm}= 88–94 GeV
41.39±0.26	1.09M	ACCIARRI 94	L3	E^{ee}_{cm}= 88–94 GeV
41.70±0.23	1.19M	AKERS 94	OPAL	E^{ee}_{cm}= 88–94 GeV
41.60±0.16	1.27M	BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
41.45±0.31	512k	ACTON 93D	OPAL	Repl. by AKERS 94
41.34±0.28	460k	ADRIANI 93M	L3	Repl. by ACCIARRI 94
41.60±0.27	520k	BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94
42 ±4	450	ABRAMS 89B	MRK2	E^{ee}_{cm}= 89.2–93.0 GeV

Z VECTOR COUPLINGS TO CHARGED LEPTONS

These quantities are the effective vector couplings of the Z to charged leptons. Their magnitude is derived from a measurement of the Z lineshape and the forward-backward lepton asymmetries as a function of energy around the Z mass. The relative sign among the vector to axial-vector couplings is obtained from a measurement of the Z asymmetry parameters, A_e and A_τ, or ν_e scattering. The fit values quoted below correspond to global nine- or five-parameter fits to lineshape, lepton forward-backward asymmetry, and A_e and A_τ measurements. See "Note on the Z boson" for details.

Within the current data set, the reason for the smallness of g^μ_V compared to g^e_V and g^τ_V is due to the large value of A_e which is heavily weighted by the SLD result. This large value of A_e leads to a large value of g^e_V. Since g^μ_V is obtained using the relation $A^\mu_{FB} = 0.75 \times A_e \times A_\mu$, a large value of g^e_V leads to a SMALL value of g^μ_V. Concerning the τ, its g_V gets mainly determined directly from A_τ which is obtained from a measurement of the τ polarization (see "Note on the Z boson").

g^e_V

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0383±0.0008 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.0414±0.0020		[120] ABE 95J	SLD	E^{ee}_{cm}= 91.31 GeV
$-0.0364^{+0.0096}_{-0.0082}$	38k	[121] ACCIARRI 94	L3	E^{ee}_{cm}= 88–94 GeV
−0.036 ±0.005	45.8k	[122] BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV
$-0.040^{+0.013}_{-0.011}$		[123] ADRIANI 93M	L3	Repl. by ACCIARRI 94
$-0.034^{+0.006}_{-0.005}$		[121] BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94

[120] ABE 95J obtain this result combining polarized Bhabha results with the A_{LR} measurement of ABE 94C. The Bhabha results alone give −0.0507 ± 0.0096 ± 0.0020.

[121] The τ polarization result has been included.

[122] BUSKULIC 94 use the added constraint of τ polarization.

[123] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.

g^μ_V

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0274±0.0047 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.0402^{+0.0153}_{-0.0211}$	34k	[124] ACCIARRI 94	L3	E^{ee}_{cm}= 88–94 GeV
−0.034 ±0.013	46.4k	[125] BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV
$-0.048^{+0.021}_{-0.033}$		[126] ADRIANI 93M	L3	Repl. by ACCIARRI 94
$-0.019^{+0.018}_{-0.019}$		[124] BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94

[124] The τ polarization result has been included.

[125] BUSKULIC 94 use the added constraint of τ polarization.

[126] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.

g^τ_V

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0378±0.0020 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.0384±0.0078	25k	[127] ACCIARRI 94	L3	E^{ee}_{cm}= 88–94 GeV
−0.038 ±0.005	45.1k	[128] BUSKULIC 94	ALEP	E^{ee}_{cm}= 88–94 GeV
−0.037 ±0.008	7441	[129] ADRIANI 93M	L3	Repl. by ACCIARRI 94
−0.039 ±0.006		[127] BUSKULIC 93J	ALEP	Repl. by BUSKULIC 94

[127] The τ polarization result has been included.

[128] BUSKULIC 94 use the added constraint of τ polarization.

[129] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.

g_V^ℓ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.0377 ± 0.0007 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.039\ \pm0.004$	50.3k	[130] ABREU	94	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.0378\,^{+0.0045}_{-0.0042}$	97k	[131] ACCIARRI	94	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.034\ \pm0.004$	146k	[130] AKERS	94	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.038\ \pm0.004$	137.3k	[130] BUSKULIC	94	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.027\ \pm0.008$	58k	[130] ACTON	93D	OPAL	Repl. by AKERS 94
$-0.040\ ^{+0.006}_{-0.005}$		[131] ADRIANI	93M	L3	Repl. by ACCIARRI 94
$-0.034\ ^{+0.004}_{-0.003}$		[131] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94

[130] Using forward-backward lepton asymmetries.

[131] The τ polarization result has been included.

Z AXIAL-VECTOR COUPLINGS TO CHARGED LEPTONS

These quantities are the effective axial-vector couplings of the Z to charged leptons. Their magnitude is derived from a measurement of the Z lineshape and the forward-backward lepton asymmetries as a function of energy around the Z mass. The relative sign among the vector to axial-vector couplings is obtained from a measurement of the Z asymmetry parameters, A_e and A_τ, or ν_e scattering. The fit values quoted below correspond to global nine- or five-parameter fits to lineshape, lepton forward-backward asymmetry, and A_e and A_τ measurements. See "Note on the Z boson" for details.

g_A^e

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.5007 ± 0.0009 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.4977 ± 0.0045		[132] ABE	95J	SLD	$E_{\rm cm}^{ee}$= 91.31 GeV
-0.4998 ± 0.0016	38k	[133] ACCIARRI	94	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.503\ \pm0.002$	45.8k	BUSKULIC	94	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
-0.4980 ± 0.0021		[133] ADRIANI	93M	L3	Repl. by ACCIARRI 94
-0.5029 ± 0.0018		[133] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94

[132] ABE 95J obtain this result combining polarized Bhabha results with the A_{LR} measurement of ABE 94C. The Bhabha results alone give $-0.4968 \pm 0.0039 \pm 0.0027$.

[133] The τ-polarization constraint has been included.

g_A^μ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.5015 ± 0.0012 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.4987\,^{+0.0030}_{-0.0026}$	34k	[134] ACCIARRI	94	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.501\ \pm0.002$	46.4k	BUSKULIC	94	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.4968\,^{+0.0050}_{-0.0037}$		[134] ADRIANI	93M	L3	Repl. by ACCIARRI 94
-0.5014 ± 0.0029		[134] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94

[134] The τ-polarization constraint has been included.

g_A^τ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.5009 ± 0.0013 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.5014 ± 0.0029	25k	[135] ACCIARRI	94	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.502\ \pm0.003$	45.1k	BUSKULIC	94	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
-0.5032 ± 0.0038	7441	[135] ADRIANI	93M	L3	Repl. by ACCIARRI 94
-0.5016 ± 0.0033		[135] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94

[135] The τ-polarization constraint has been included.

g_A^ℓ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.5008 ± 0.0008 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.4999 ± 0.0014	71k	ABREU	94	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
-0.4998 ± 0.0014	97k	[136] ACCIARRI	94	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.500\ \pm0.001$	146k	AKERS	94	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$-0.502\ \pm0.001$	137k	BUSKULIC	94	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
-0.4998 ± 0.0016	58k	ACTON	93D	OPAL	Repl. by AKERS 94
-0.4986 ± 0.0015		[136] ADRIANI	93M	L3	Repl. by ACCIARRI 94
-0.5022 ± 0.0015		[136] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94

[136] The τ-polarization constraint has been included.

Z COUPLINGS TO NEUTRAL LEPTONS

These quantities are the effective couplings of the Z to neutral leptons. $\nu_e e$ and $\nu_\mu e$ scattering results are combined with g_A^e and g_V^e measurements at the Z mass to obtain g^{ν_e} and g^{ν_μ} following NOVIKOV 93C.

g^{ν_e}

VALUE	DOCUMENT ID		TECN	COMMENT
0.528 ± 0.085	[137] VILAIN	94	CHM2	From $\nu_\mu e$ and $\nu_e e$ scattering

[137] VILAIN 94 derive this value from their value of g^{ν_μ} and their ratio $g^{\nu_e}/g^{\nu_\mu} = 1.05\,^{+0.15}_{-0.18}$.

g^{ν_μ}

VALUE	DOCUMENT ID		TECN	COMMENT
0.502 ± 0.017	[138] VILAIN	94	CHM2	From $\nu_\mu e$ scattering

[138] VILAIN 94 derive this value from their measurement of the couplings $g_A^{e\nu_\mu} = -0.503 \pm 0.017$ and $g_V^{e\nu_\mu} = -0.035 \pm 0.017$ obtained from $\nu_\mu e$ scattering. We have re-evaluated this value using the current PDG values for g_A^e and g_V^e.

Z ASYMMETRY PARAMETERS

For each fermion-antifermion pair coupling to the Z these quantities are defined as

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

where g_V^f and g_A^f are the effective vector and axial-vector couplings. For their relation to the various lepton asymmetries see the 'Note on the Z Boson.'

A_e

Using polarized beams, this quantity can also be measured as $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$, where σ_L and σ_R are the e^+e^- production cross sections for Z bosons produced with left-handed and right-handed electrons respectively.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1519 ± 0.0034 OUR AVERAGE					
$0.162\ \pm0.041\ \pm0.014$	89838	[139] ABE	97	SLD	$E_{\rm cm}^{ee}$= 91.27 GeV
0.1543 ± 0.0039	93644	[140] ABE	97E	SLD	$E_{\rm cm}^{ee}$= 91.27 GeV
$0.152\ \pm0.012$		[141] ABE	97N	SLD	$E_{\rm cm}^{ee}$= 91.27 GeV
$0.129\ \pm0.014\ \pm0.005$	89075	[142] ALEXANDER	96U	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
$0.202\ \pm0.038\ \pm0.008$		[143] ABE	95J	SLD	$E_{\rm cm}^{ee}$= 91.31 GeV
$0.136\ \pm0.027\ \pm0.003$		[144] ABREU	95I	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
$0.129\ \pm0.016\ \pm0.005$	33000	[145] BUSKULIC	95Q	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
$0.157\ \pm0.020\ \pm0.005$	86000	[144] ACCIARRI	94E	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.122\ \pm0.030\ \pm0.012$	30663	[144] AKERS	95	OPAL	Repl. by ALEXANDER 96U
$0.1656\pm0.0071\pm0.0028$	49392	[146] ABE	94C	SLD	Repl. by ABE 97E
$0.097\ \pm0.044\ \pm0.004$	10224	[147] ABE	93	SLD	Repl. by ABE 97E
$0.120\ \pm0.026$		[144] BUSKULIC	93P	ALEP	Repl. by BUSKULIC 95Q

[139] ABE 97 obtain this result from a measurement of the observed left-right charge asymmetry, $A_Q^{\rm obs} = 0.225 \pm 0.056 \pm 0.019$, in hadronic Z decays. If they combine this value of $A_Q^{\rm obs}$ with their earlier measurement of $A_{LR}^{\rm obs}$ they determine A_e to be $0.1574 \pm 0.0197 \pm 0.0067$ independent of the beam polarization.

[140] ABE 97E measure the left-right asymmetry in hadronic Z production. This value (statistical and systematic errors added in quadrature) leads to $\sin^2\theta_W^{\rm eff} = 0.23060 \pm 0.00050$.

[141] ABE 97N obtain this direct measurement using the lef-right cross section asymmetry and the left-right forward-backward asymmetry in leptonic decays of the Z boson obtained with a polarized electron beam.

[142] ALEXANDER 96U measure the τ-lepton polarization and the forward-backward polarization asymmetry.

[143] ABE 95J obtain this result from polarized Bhabha scattering.

[144] Derived from the measurement of forward-backward τ polarization asymmetry.

[145] BUSKULIC 95Q obtain this result fitting the τ polarization as a function of the polar τ production angle.

[146] ABE 94C measured the left-right asymmetry in Z production. This value leads to $\sin^2\theta_W = 0.2292 \pm 0.0009 \pm 0.0004$.

[147] ABE 93 measured the left-right asymmetry in Z production.

A_μ

This quantity is directly extracted from a measurement of the left-right forward-backward asymmetry in $\mu^+\mu^-$ production at SLC using a polarized electron beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.102 ± 0.034	3788	[148] ABE	97N	SLD	$E_{\rm cm}^{ee}$= 91.27 GeV

[148] ABE 97N obtain this direct measurement using the lef-right cross section asymmetry and the left-right forward-backward asymmetry in $\mu^+\mu^-$ decays of the Z boson obtained with a polarized electron beam.

A_τ

The LEP Collaborations derive this quantity from the measurement of the average τ polarization in $Z \rightarrow \tau^+\tau^-$. The SLD Collaboration directly extracts this quantity from its measured left-right forward-backward asymmetry in $Z \rightarrow \tau^+\tau^-$ produced using a polarized e^- beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.143±0.008 OUR AVERAGE				
0.195±0.034		[149] ABE 97N	SLD	E^{ee}_{cm}= 91.27 GeV
0.134±0.009±0.010	89075	[150] ALEXANDER 96U	OPAL	E^{ee}_{cm}= 88–94 GeV
0.148±0.017±0.014		ABREU 95I	DLPH	E^{ee}_{cm}= 88–94 GeV
0.136±0.012±0.009	33000	[151] BUSKULIC 95Q	ALEP	E^{ee}_{cm}= 88–94 GeV
0.150±0.013±0.009	86000	ACCIARRI 94E	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.153±0.019±0.013	30663	AKERS 95	OPAL	Repl. by ALEXANDER 96U
0.132±0.033	10732	ADRIANI 93M	L3	Repl. by ACCIARRI 94E
0.143±0.023		BUSKULIC 93P	ALEP	Repl. by BUSKULIC 95Q
0.24 ±0.07	2021	ABREU 92N	DLPH	Repl. by ABREU 95I

[149] ABE 97N obtain this direct measurement using the left-right cross section asymmetry and the left-right forward-backward asymmetry in $\tau^+\tau^-$ decays of the Z boson obtained with a polarized electron beam.

[150] ALEXANDER 96U measure the τ-lepton polarization and the forward-backward polarization asymmetry.

[151] BUSKULIC 95Q obtain this result fitting the τ polarization as a function of the polar τ production angle.

A_c

This quantity is directly extracted from a measurement of the left-right forward-backward asymmetry in $c\overline{c}$ production at SLC using polarized electron beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	DOCUMENT ID	TECN	COMMENT
0.59±0.19 OUR AVERAGE			
0.37±0.23±0.21	[152] ABE 95L	SLD	E^{ee}_{cm}= 91.26 GeV
0.73±0.22±0.10	[153] ABE,K 95	SLD	E^{ee}_{cm}= 91.26 GeV

[152] ABE 95L tag b and c quarks through their semileptonic decays into electrons and muons. A maximum likelihood fit is performed to extract A_b and A_c.

[153] ABE,K 95 tag $Z \rightarrow c\overline{c}$ events using D^{*+} and D^+ meson production. To take care of the $b\overline{b}$ contamination in their analysis they use A_b^D= 0.64 ± 0.11 (which is A_b from D^*/D tagging). This is obtained by starting with a Standard Model value of 0.935, assigning it an estimated error of ±0.105 to cover LEP and SLD measurements, and finally taking into account B-$\overline{B}$ mixing ($1-2\chi_{\text{mix}}$ = 0.72 ± 0.09). Combining with ABE 95L they quote 0.59 ± 0.19.

A_b

This quantity is directly extracted from a measurement of the left-right forward-backward asymmetry in $b\overline{b}$ production at SLC using polarized electron beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.89±0.11 OUR AVERAGE				
0.87±0.11±0.09	4032	[154] ABE 95K	SLD	E^{ee}_{cm}= 91.26 GeV
0.91±0.14±0.07		[155] ABE 95L	SLD	E^{ee}_{cm}= 91.26 GeV

[154] ABE 95K obtain an enriched sample of $b\overline{b}$ events tagging with the impact parameter. A momentum-weighted charge sum is used to identify the charge of the underlying b quark.

[155] ABE 95L tag b and c quarks through their semileptonic decays into electrons and muons. A maximum likelihood fit is performed to extract A_b and A_c. Combining with ABE 95K, they quote 0.89 ± 0.09 ± 0.06.

TRANSVERSE SPIN CORRELATIONS IN $Z \rightarrow \tau^+\tau^-$

The correlations between the transverse spin components of $\tau^+\tau^-$ produced in Z decays may be expressed in terms of the vector and axial-vector couplings:

$$C_{TT} = \frac{|g_A^\tau|^2 - |g_V^\tau|^2}{|g_A^\tau|^2 + |g_V^\tau|^2}$$

$$C_{TN} = -2\frac{|g_A^\tau||g_V^\tau|}{|g_A^\tau|^2 + |g_V^\tau|^2}\sin(\Phi_{g_V^\tau} - \Phi_{g_A^\tau})$$

C_{TT} refers to the transverse-transverse (within the collision plane) spin correlation and C_{TN} refers to the transverse-normal (to the collision plane) spin correlation.

The longitudinal τ polarization P_τ $(= -A_\tau)$ is given by:

$$P_\tau = -2\frac{|g_A^\tau||g_V^\tau|}{|g_A^\tau|^2 + |g_V^\tau|^2}\cos(\Phi_{g_V^\tau} - \Phi_{g_A^\tau})$$

Here Φ is the phase and the phase difference $\Phi_{g_V^\tau} - \Phi_{g_A^\tau}$ can be obtained using both the measurements of C_{TN} and P_τ.

C_{TT}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.01±0.12 OUR AVERAGE				
$0.87\pm0.20^{+0.10}_{-0.12}$	9.1K	ABREU 97G	DLPH	E^{ee}_{cm}= 91.2 GeV
1.06±0.13±0.05	120K	BARATE 97D	ALEP	E^{ee}_{cm}= 91.2 GeV

C_{TN}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.08±0.13±0.04	120K	[156] BARATE 97D	ALEP	E^{ee}_{cm}= 91.2 GeV

[156] BARATE 97D combine their value of C_{TN} with the world average $P_\tau = -0.140 \pm 0.007$ to obtain $\tan(\Phi_{g_V^\tau} - \Phi_{g_A^\tau}) = -0.57 \pm 0.97$.

$A_{FB}^{(0,e)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow e^+e^-$

For the Z peak, we report the pole asymmetry defined by $(3/4)A_e^2$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
1.51±0.40 OUR FIT				
1.5 ±0.4 OUR AVERAGE				
2.5 ±0.9		91.2	ABREU 94	DLPH
1.04±0.92		91.2	ACCIARRI 94	L3
0.62±0.80		91.2	AKERS 94	OPAL
1.85±0.66		91.2	BUSKULIC 94	ALEP

$A_{FB}^{(0,\mu)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow \mu^+\mu^-$

For the Z peak, we report the pole asymmetry defined by $(3/4)A_eA_\mu$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
1.33± 0.26 OUR FIT				
1.34± 0.24 OUR AVERAGE				
1.4 ± 0.5		91.2	ABREU 94	DLPH
1.79± 0.61		91.2	ACCIARRI 94	L3
0.99± 0.42		91.2	AKERS 94	OPAL
1.46± 0.48		91.2	BUSKULIC 94	ALEP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9 ±30	−2	20	[157] ABREU 95M	DLPH
7 ±26	−10	40	[157] ABREU 95M	DLPH
−11 ±33	−25	57	[157] ABREU 95M	DLPH
−62 ±17	−45	69	[157] ABREU 95M	DLPH
−56 ±10	−58	79	[157] ABREU 95M	DLPH
−13 ± 5	−23	87.5	[157] ABREU 95M	DLPH
$-29.0\ ^{+5.0}_{-4.8}\ \pm0.5$	−32.1	56.9	[158] ABE 90I	VNS
− 9.9 ± 1.5 ±0.5	−9.2	35	HEGNER 90	JADE
0.05± 0.22	0.026	91.14	[159] ABRAMS 89D	MRK2
−43.4 ±17.0	−24.9	52.0	[160] BACALA 89	AMY
−11.0 ±16.5	−29.4	55.0	[160] BACALA 89	AMY
−30.0 ±12.4	−31.2	56.0	[160] BACALA 89	AMY
−46.2 ±14.9	−33.0	57.0	[160] BACALA 89	AMY
−29 ±13	−25.9	53.3	ADACHI 88C	TOPZ
+ 5.3 ± 5.0 ±0.5	−1.2	14.0	ADEVA 88	MRKJ
−10.4 ± 1.3 ±0.5	−8.6	34.8	ADEVA 88	MRKJ
−12.3 ± 5.3 ±0.5	−10.7	38.3	ADEVA 88	MRKJ
−15.6 ± 3.0 ±0.5	−14.9	43.8	ADEVA 88	MRKJ
− 1.0 ± 6.0	−1.2	13.9	BRAUNSCH... 88D	TASS
− 9.1 ± 2.3 ±0.5	−8.6	34.5	BRAUNSCH... 88D	TASS
$-10.6\ ^{+2.2}_{-2.3}\ \pm0.5$	−8.9	35.0	BRAUNSCH... 88D	TASS
$-17.6\ ^{+4.4}_{-4.3}\ \pm0.5$	−15.2	43.6	BRAUNSCH... 88D	TASS
− 4.8 ± 6.5 ±1.0	−11.5	39	BEHREND 87C	CELL
−18.8 ± 4.5 ±1.0	−15.5	44	BEHREND 87C	CELL
+ 2.7 ± 4.9	−1.2	13.9	BARTEL 86C	JADE
−11.1 ± 1.8 ±1.0	−8.6	34.4	BARTEL 86C	JADE
−17.3 ± 4.8 ±1.0	−13.7	41.5	BARTEL 86C	JADE
−22.8 ± 5.1 ±1.0	−16.6	44.8	BARTEL 86C	JADE
− 6.3 ± 0.8 ±0.2	−6.3	29	ASH 85	MAC
− 4.9 ± 1.5 ±0.5	−5.9	29	DERRICK 85	HRS
− 7.1 ± 1.7	−5.7	29	LEVI 83	MRK2
−16.1 ± 3.2	−9.2	34.2	BRANDELIK 82C	TASS

[157] ABREU 95M perform this measurement using radiative muon-pair events associated with high-energy isolated photons.

[158] ABE 90I measurements in the range $50 \leq \sqrt{s} \leq 60.8$ GeV.

[159] ABRAMS 89D asymmetry includes both 9 $\mu^+\mu^-$ and 15 $\tau^+\tau^-$ events.

[160] BACALA 89 systematic error is about 5%.

$A_{FB}^{(0,\tau)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow \tau^+\tau^-$

For the *Z* peak, we report the pole asymmetry defined by $(3/4)A_e A_\tau$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the *Z* boson."

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
2.12± 0.32 OUR FIT				
2.13± 0.31 OUR AVERAGE				
2.2 ± 0.7		91.2	ABREU 94	DLPH
2.65± 0.88		91.2	ACCIARRI 94	L3
2.05± 0.52		91.2	AKERS 94	OPAL
1.97± 0.56		91.2	BUSKULIC 94	ALEP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-32.8\ ^{+6.4}_{-6.2}$ ±1.5	−32.1	56.9	[161] ABE 90I	VNS
− 8.1 ± 2.0 ±0.6	−9.2	35	HEGNER 90	JADE
−18.4 ±19.2	−24.9	52.0	[162] BACALA 89	AMY
−17.7 ±26.1	−29.4	55.0	[162] BACALA 89	AMY
−45.9 ±16.6	−31.2	56.0	[162] BACALA 89	AMY
−49.5 ±18.0	−33.0	57.0	[162] BACALA 89	AMY
−20 ±14	−25.9	53.3	ADACHI 88C	TOPZ
−10.6 ± 3.1 ±1.5	−8.5	34.7	ADEVA 88	MRKJ
− 8.5 ± 6.6 ±1.5	−15.4	43.8	ADEVA 88	MRKJ
− 6.0 ± 2.5 ±1.0	8.8	34.6	BARTEL 85F	JADE
−11.8 ± 4.6 ±1.0	14.8	43.0	BARTEL 85F	JADE
− 5.5 ± 1.2 ±0.5	−0.063	29.0	FERNANDEZ 85	MAC
− 4.2 ± 2.0	0.057	29	LEVI 83	MRK2
−10.3 ± 5.2	−9.2	34.2	BEHREND 82	CELL
− 0.4 ± 6.6	−9.1	34.2	BRANDELIK 82C	TASS

[161] ABE 90I measurements in the range 50 ≤ $\sqrt{s}$ ≤ 60.8 GeV.

[162] BACALA 89 systematic error is about 5%.

$A_{FB}^{(0,\ell)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow \ell^+\ell^-$

For the *Z* peak, we report the pole asymmetry defined by $(3/4)A_\ell^2$ as determined by the five-parameter fit to cross-section and lepton forward-backward asymmetry data assuming lepton universality. For details see the "Note on the *Z* boson."

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
1.59±0.18 OUR FIT				
1.60±0.18 OUR AVERAGE				
1.77±0.37		91.2	ABREU 94	DLPH
1.84±0.45		91.2	ACCIARRI 94	L3
1.28±0.30		91.2	AKERS 94	OPAL
1.71±0.33		91.2	BUSKULIC 94	ALEP

$A_{FB}^{(0,u)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow u\overline{u}$

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
4.0±7.3 OUR EVALUATION				
4.0 ± 6.7 ± 2.8	6	91.2	[163] ACKERSTAFF 97T	OPAL

[163] ACKERSTAFF 97T measure the forward-backward asymmetry of various fast hadrons made of light quarks. Then using SU(2) isospin symmetry and flavor independence for down and strange quarks authors solve for the different quark types.

$A_{FB}^{(0,s)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow s\overline{s}$

The *s*-quark asymmetry is derived from measurements of the forward-backward asymmetry of fast hadrons containing an *s* quark.

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
9.9±3.1 OUR AVERAGE Error includes scale factor of 1.2.				
6.8±3.5±1.1	10	91.2	[164] ACKERSTAFF 97T	OPAL
13.1±3.5±1.3		91.2	[165] ABREU 95G	DLPH

[164] ACKERSTAFF 97T measure the forward-backward asymmetry of various fast hadrons made of light quarks. Then using SU(2) isospin symmetry and flavor independence for down and strange quarks authors solve for the different quark types. The value reported here corresponds then to the forward-backward asymmetry for "down-type" quarks.

[165] ABREU 95G require the presence of a high-momentum charged kaon or Λ^0 to tag the *s* quark. An unresolved *s*- and *d*-quark asymmetry of (11.2 ± 3.1 ± 5.4)% is obtained by tagging the presence of a high-energy neutron or neutral kaon in the hadron calorimeter.

$A_{FB}^{(0,c)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow c\overline{c}$

OUR FIT, which is obtained by a simultaneous fit to several *c*- and *b*-quark measurements as explained in the "Note on the *Z* boson," refers to the *Z* pole asymmetry. As a cross check we have also performed a weighted average of the "near peak" measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. Applying to this combined "peak" measurement QCD, QED, and energy-dependence corrections, our weighted average gives a pole asymmetry of (7.20 ± 0.64)%.

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
7.32± 0.58 OUR FIT				
6.3 ± 1.2 ±0.6		91.22	[166] ALEXANDER 97C	OPAL
6.00± 0.67±0.52		91.24	[167] ALEXANDER 96	OPAL
7.7 ± 2.9 ±1.2		91.27	[168] ABREU 95E	DLPH
8.3 ± 2.2 ±1.6		91.27	[169] ABREU 95K	DLPH
6.99± 2.05±1.02		91.24	[170] BUSKULIC 95I	ALEP
9.9 ± 2.0 ±1.7		91.24	[171] BUSKULIC 94G	ALEP
8.3 ± 3.8 ±2.7	5.6	91.24	[172] ADRIANI 92D	L3
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9 ± 5.1 ±0.9		89.45	[166] ALEXANDER 97C	OPAL
15.8 ± 4.1 ±1.1		93.00	[166] ALEXANDER 97C	OPAL
− 7.5 ± 3.4 ±0.6	−3.5	89.52	[167] ALEXANDER 96	OPAL
14.1 ± 2.8 ±0.9	12.0	92.94	[167] ALEXANDER 96	OPAL
6.8 ± 4.2 ±0.9		91.25	[173] BUSKULIC 94J	ALEP
1.4 ± 3.0 ±2.0	5.6	91.24	[174] ACTON 93K	OPAL
3.8 ± 4.4 ±1.0	5.4	91.28	[175] AKERS 93D	OPAL
−12.9 ± 7.8 ±5.5	−13.6	35	BEHREND 90D	CELL
7.7 ±13.4 ±5.0	−22.1	43	BEHREND 90D	CELL
−12.8 ± 4.4 ±4.1	−13.6	35	ELSEN 90	JADE
−10.9 ±12.9 ±4.6	−23.2	44	ELSEN 90	JADE
−14.9 ± 6.7	−13.3	35	OULD-SAADA 89	JADE

[166] ALEXANDER 97C identify the *b* and *c* events using a D/D^* tag.

[167] ALEXANDER 96 tag heavy flavors using one or two identified leptons. This allows the simultaneous fitting of the *b* and *c* quark forward-backward asymmetries as well as the average B^0-$\overline{B}^0$ mixing.

[168] ABREU 95E require the presence of a $D^{*\pm}$ to identify *c* and *b* quarks.

[169] ABREU 95K identify *c* and *b* quarks using both electron and muon semileptonic decays.

[170] BUSKULIC 95I require the presence of a high momentum $D^{*\pm}$ to have an enriched sample of $Z \rightarrow c\overline{c}$ events.

[171] BUSKULIC 94G perform a simultaneous fit to the *p* and p_T spectra of both single and dilepton events.

[172] ADRIANI 92D use both electron and muon semileptonic decays.

[173] BUSKULIC 94J identify the *b* and *c* decays using D^*. Replaced by BUSKULIC 95I.

[174] ACTON 93K use the lepton tagging technique. Replaced by ALEXANDER 96.

[175] AKERS 93D identify the *b* and *c* decays using D^*. Replaced by ALEXANDER 97C.

$A_{FB}^{(0,b)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow b\overline{b}$

OUR FIT, which is obtained by a simultaneous fit to several *c*- and *b*-quark measurements as explained in the "Note on the *Z* boson," refers to the *Z* pole asymmetry. As a cross check we have also performed a weighted average of the "near peak" measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. Applying to this combined "peak" measurement QCD, QED, and energy-dependence corrections, our weighted average gives a pole asymmetry of (10.07 ± 0.32)%. For the jet-charge measurements (where the QCD corrections are already included since they represent an inherent part of the analysis), we subtract the QCD correction before combining.

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
10.02± 0.28 OUR FIT				
9.94± 0.52± 0.44		91.21	[176] ACKERSTAFF 97P	OPAL
9.4 ± 2.7 ± 2.2		91.22	[177] ALEXANDER 97C	OPAL
9.06± 0.51± 0.23		91.24	[178] ALEXANDER 96	OPAL
9.65± 0.44± 0.26		91.21	[179] BUSKULIC 96Q	ALEP
5.9 ± 6.2 ± 2.4		91.27	[180] ABREU 95E	DLPH
10.4 ± 1.3 ± 0.5		91.27	[181] ABREU 95K	DLPH
11.5 ± 1.7 ± 1.0		91.27	[182] ABREU 95K	DLPH
8.7 ± 1.1 ± 0.4		91.3	[183] ACCIARRI 94D	L3
9.92± 0.84± 0.46		91.19	[184] BUSKULIC 94I	ALEP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.1 ± 2.1 ± 0.2		89.44	[176] ACKERSTAFF 97P	OPAL
14.5 ± 1.7 ± 0.7		92.91	[176] ACKERSTAFF 97P	OPAL
− 8.6 ±10.8 ± 2.9		89.45	[177] ALEXANDER 97C	OPAL
− 2.1 ± 9.0 ± 2.6		93.00	[177] ALEXANDER 97C	OPAL
5.5 ± 2.4 ± 0.3	5.5	89.52	[178] ALEXANDER 96	OPAL
11.7 ± 2.0 ± 0.3	11.4	92.94	[178] ALEXANDER 96	OPAL
− 3.4 ±11.2 ± 0.7		88.38	[179] BUSKULIC 96Q	ALEP
5.3 ± 2.0 ± 0.2		89.38	[179] BUSKULIC 96Q	ALEP
8.9 ± 5.9 ± 0.4		90.21	[179] BUSKULIC 96Q	ALEP
3.8 ± 5.1 ± 0.2		92.05	[179] BUSKULIC 96Q	ALEP
10.3 ± 1.6 ± 0.4		92.94	[179] BUSKULIC 96Q	ALEP

$8.8 \pm 7.5 \pm 0.5$		93.90	[179] BUSKULIC	96Q ALEP
$6.2 \pm 3.4 \pm 0.2$		89.52	[185] AKERS	95S OPAL
$9.63 \pm 0.67 \pm 0.38$		91.25	[185] AKERS	95S OPAL
$17.2 \pm 2.8 \pm 0.7$		92.94	[185] AKERS	95S OPAL
$8.7 \pm 1.4 \pm 0.2$		91.24	[186] BUSKULIC	94G ALEP
$7.1 \pm 5.4 \pm 0.7$	5.2	89.66	[187] ACTON	93K OPAL
$9.2 \pm 1.8 \pm 0.8$	8.5	91.24	[187] ACTON	93K OPAL
$13.1 \pm 4.7 \pm 1.3$	10.8	92.75	[187] ACTON	93K OPAL
$13.9 \pm 9.7 \pm 4.9$	9.4	91.28	[188] AKERS	93D OPAL
$16.1 \pm 6.0 \pm 2.1$		91.2	[189] ABREU	92H DLPH
$8.6 \pm 1.5 \pm 0.7$	8.2	91.24	[190] ADRIANI	92D L3
$2.5 \pm 5.1 \pm 0.7$	5.3	89.67	[191] ADRIANI	92D L3
$9.7 \pm 1.7 \pm 0.7$	8.2	91.24	[191] ADRIANI	92D L3
$6.2 \pm 4.2 \pm 0.7$	10.8	92.81	[191] ADRIANI	92D L3
$-71 \pm 34 {}^{+7}_{-8}$	-58	58.3	SHIMONAKA	91 TOPZ
$-22.2 \pm 7.7 \pm 3.5$	-26.0	35	BEHREND	90D CELL
$-49.1 \pm 16.0 \pm 5.0$	-39.7	43	BEHREND	90D CELL
-28 ± 11	-23	35	BRAUNSCH...	90 TASS
$-16.6 \pm 7.7 \pm 4.8$	-24.3	35	ELSEN	90 JADE
$-33.6 \pm 22.2 \pm 5.2$	-39.9	44	ELSEN	90 JADE
$3.4 \pm 7.0 \pm 3.5$	-16.0	29.0	BAND	89 MAC
$-72 \pm 28 \pm 13$	-56	55.2	SAGAWA	89 AMY

[176] ACKERSTAFF 97P tag b quarks using lifetime. The quark charge is measured using both jet charge and vertex charge, a weighted sum of the charges of tracks in a jet which contains a tagged secondary vertex.

[177] ALEXANDER 97C identify the b and c events using a D/D^* tag.

[178] ALEXANDER 96 tag heavy flavors using one or two identified leptons. This allows the simultaneous fitting of the b and c quark forward-backward asymmetries as well as the average B^0-$\overline{B}^0$ mixing.

[179] BUSKULIC 96Q tag b-quark flavor and charge using high transverse momentum leptons. The asymmetry value at the Z peak is obtained using a charm charge asymmetry of 6.17%.

[180] ABREU 95E require the presence of a $D^{*\pm}$ to identify c and b quarks.

[181] ABREU 95K identify c and b quarks using both electron and muon semileptonic decays. The systematic error includes an uncertainty of ± 0.3 due to the mixing correction ($\chi = 0.115 \pm 0.011$).

[182] ABREU 95K tag b quarks using lifetime; the quark charge is identified using jet charge. The systematic error includes an uncertainty of ± 0.3 due to the mixing correction ($\chi = 0.115 \pm 0.011$).

[183] ACCIARRI 94D use both electron and muon semileptonic decays.

[184] BUSKULIC 94I use the lifetime tag method to obtain a high purity sample of $Z \to b\overline{b}$ events and the hemisphere charge technique to obtain the jet charge.

[185] AKERS 95S tag b quarks using lifetime; the quark charge is measured using jet charge. These asymmetry values are obtained using $R_b = \Gamma(b\overline{b})/\Gamma(\text{hadrons}) = 0.216$. For a value of R_b different from this by an amount ΔR_b, the change in the asymmetry values is given by $-K\Delta R_b$, where $K = 0.082$, 0.471, and 0.855 for $\sqrt{s}$ values of 89.52, 91.25, and 92.94 GeV respectively. Replaced by ACKERSTAFF 97P.

[186] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events. Replaced by BUSKULIC 96Q.

[187] ACTON 93K use the lepton tagging technique. The systematic error includes the uncertainty on the mixing parameter. Replaced by ALEXANDER 96.

[188] AKERS 93D identify the b and c decays using D^*. Replaced by ALEXANDER 97C.

[189] B tagging via its semimuonic decay. Experimental value corrected using average LEP B^0-$\overline{B}^0$ mixing parameter $\chi = 0.143 \pm 0.023$.

[190] ADRIANI 92D use both electron and muon semileptonic decays. For this measurement ADRIANI 92D average over all $\sqrt{s}$ values to obtain a single result.

[191] ADRIANI 92D use both electron and muon semileptonic decays. The quoted systematic error is common to all measurements. The peak value is superseded by ACCIARRI 94D.

CHARGE ASYMMETRY IN $e^+e^- \to q\overline{q}$

Summed over five lighter flavors.

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on B^0-$\overline{B}^0$ mixing and on other electroweak parameters.

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.76 \pm 0.12 \pm 0.15$		91.2	[192] ABREU	92I DLPH
$4.0 \pm 0.4 \pm 0.63$	4.0	91.3	[193] ACTON	92L OPAL
$9.1 \pm 1.4 \pm 1.6$	9.0	57.9	ADACHI	91 TOPZ
$-0.84 \pm 0.15 \pm 0.04$		91	DECAMP	91B ALEP
$8.3 \pm 2.9 \pm 1.9$	8.7	56.6	STUART	90 AMY
$11.4 \pm 2.2 \pm 2.1$	8.7	57.6	ABE	89L VNS
6.0 ± 1.3	5.0	34.8	GREENSHAW	89 JADE
8.2 ± 2.9	8.5	43.6	GREENSHAW	89 JADE

[192] ABREU 92I has 0.14 systematic error due to uncertainty of quark fragmentation.

[193] ACTON 92L use the weight function method on 259k selected $Z \to$ hadrons events. The systematic error includes a contribution of 0.2 due to B^0-$\overline{B}^0$ mixing effect, 0.4 due to Monte Carlo (MC) fragmentation uncertainties and 0.3 due to MC statistics. ACTON 92L derive a value of $\sin^2\theta_W^{\rm eff}$ to be $0.2321 \pm 0.0017 \pm 0.0028$.

CHARGE ASYMMETRY IN $p\overline{p} \to Z \to e^+e^-$

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$5.2 \pm 5.9 \pm 0.4$		91	ABE	91E CDF

Z REFERENCES

ABE	98D	PRL 80 660	K. Abe+	(SLD Collab.)
ACKERSTAFF	98E	EPJ C1 439	K. Ackerstaff+	(OPAL Collab.)
ABE	97	PRL 78 17	+Abe, Abt, Akagi, Allen+	(SLD Collab.)
ABE	97E	PRL 78 2075	+Abe, Abt, Akagi, Allen+	(SLD Collab.)
ABE	97N	PRL 79 804	K. Abe+	(SLD Collab.)
ABREU	97C	ZPHY C73 243	+Adam, Adye, Ajinenko+	(DELPHI Collab.)
ABREU	97G	PL B404 194	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97D	PL B393 465	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	97J	PL B407 351	M. Acciarri+	(L3 Collab.)
ACCIARRI	97K	PL B407 361	M. Acciarri+	(L3 Collab.)
ACCIARRI	97L	PL B407 389	M. Acciarri+	(L3 Collab.)
ACCIARRI	97R	PL B413 167	M. Acciarri+	(L3 Collab.)
ACKERSTAFF	97C	PL B391 221	+Alexander, Allison, Altekamp, Ametewee+	(OPAL Collab.)
ACKERSTAFF	97K	ZPHY C74 1	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97M	ZPHY C74 413	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97P	ZPHY C75 385	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97S	PL B412 210	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97T	ZPHY C76 387	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97W	ZPHY C76 425	K. Ackerstaff+	(OPAL Collab.)
ALEXANDER	97C	ZPHY C73 379	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	97D	ZPHY C73 569	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	97E	ZPHY C73 587	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BARATE	97D	PL B405 191	R. Barate+	(ALEPH Collab.)
BARATE	97E	PL B401 150	R. Barate+	(ALEPH Collab.)
BARATE	97F	PL B401 163	R. Barate+	(ALEPH Collab.)
BARATE	97J	ZPHY C74 451	R. Barate+	(ALEPH Collab.)
ABE	96E	PR D53 1023	+Abt, Ahn, Akagi, Allen+	(SLD Collab.)
ABREU	96	ZPHY C70 531	+Adam, Adye+	(DELPHI Collab.)
ABREU	96C	PL B379 309	+Adam, Adye+	(DELPHI Collab.)
ABREU	96R	ZPHY C72 31	+Adam, Adye+	(DELPHI Collab.)
ABREU	96S	PL B389 405	+Adam, Adye, Ajinenko+	(DELPHI Collab.)
ABREU	96U	ZPHY C73 61	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	96	PL B371 126	+Adam, Adriani+	(L3 Collab.)
ACCIARRI	96B	PL B370 195	+Adam, Adriani+	(L3 Collab.)
ADAM	96	ZPHY C69 561	+Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ADAM	96B	ZPHY C70 371	+Adye, Agasi+	(DELPHI Collab.)
ALEXANDER	96	ZPHY C70 357	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96B	ZPHY C70 197	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96F	PL B370 185	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96N	PL B384 343	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96R	ZPHY C72 1	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96U	ZPHY C72 365	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96X	PL B376 232	G. Alexander+	(OPAL Collab.)
BUSKULIC	96D	ZPHY C69 393	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	96H	ZPHY C69 379	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	96Q	PL B384 414	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABE	95J	PRL 74 2880	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE	95K	PRL 74 2890	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE	95L	PRL 74 2895	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE,K	95	PRL 75 3609	K. Abe, Abt, Ahn, Akagi+	(SLD Collab.)
ABREU	95	ZPHY C65 709 erratum	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95D	ZPHY C66 323	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95E	ZPHY C66 341	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95F	NP B444 3	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95G	ZPHY C67 1	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95I	ZPHY C67 183	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95J	ZPHY C65 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95K	ZPHY C65 569	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95L	ZPHY C65 587	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95M	ZPHY C65 603	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	95O	ZPHY C67 543	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95R	ZPHY C68 353	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95W	PL B361 207	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95X	ZPHY C69 1	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	95B	PL B345 589	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95C	PL B345 609	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95G	PL B353 136	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AKERS	95	ZPHY C65 1	+Alexander, Allison+	(OPAL Collab.)
AKERS	95B	ZPHY C65 17	+Alexander, Allison+	(OPAL Collab.)
AKERS	95C	ZPHY C65 47	+Alexander, Allison+	(OPAL Collab.)
AKERS	95O	ZPHY C67 27	+Alexander, Allison+	(OPAL Collab.)
AKERS	95S	ZPHY C67 365	+Alexander, Allison+	(OPAL Collab.)
AKERS	95U	ZPHY C67 389	+Alexander, Allison+	(OPAL Collab.)
AKERS	95W	ZPHY C67 555	+Alexander, Allison+	(OPAL Collab.)
AKERS	95X	ZPHY C68 1	+Alexander, Allison+	(OPAL Collab.)
AKERS	95Z	ZPHY C68 203	+Alexander, Allison+	(OPAL Collab.)
ALEXANDER	95D	PL B358 162	+Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	95I	PL B352 479	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	95Q	ZPHY C69 183	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	95R	ZPHY C69 15	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
MIYABAYASHI	95	PL B347 171	+Adachi, Fujii+	(TOPAZ Collab.)
ABE	94C	PRL 73 25	+Abt, Ash, Aston, Bacchetta, Baird+	(SLD Collab.)
ABREU	94	NP B418 403	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	94B	PL B327 386	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	94P	PL B341 109	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	94	ZPHY C62 551	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	94B	PL B328 223	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	94D	PL B335 542	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	94E	PL B341 245	+Adam, Adriani+	(L3 Collab.)
AKERS	94	ZPHY C61 19	+Alexander, Allison+	(OPAL Collab.)
AKERS	94P	ZPHY C63 181	+Alexander, Allison+	(OPAL Collab.)
BUSKULIC	94	ZPHY C62 539	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	94G	ZPHY C62 179	+Casper, De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	94I	PL B335 99	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	94J	ZPHY C62 1	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	94K	ZPHY C64 361	+De Bonis, Decamp+	(ALEPH Collab.)
VILAIN	94	PL B320 203	+Wilquet, Beyer+	(CHARM II Collab.)
ABE	93	PRL 70 2515	+Abt, Acton+	(SLD Collab.)
ABREU	93	PL B298 236	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	93I	ZPHY C59 533	+Adam, Adye, Agasi+	(DELPHI Collab.)
Also	95	ZPHY C65 709 erratum	Abreu, Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	93L	PL B318 249	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	93	PL B305 407	+Alexander, Allison+	(OPAL Collab.)
ACTON	93D	ZPHY C58 219	+Alexander, Allison+	(OPAL Collab.)
ACTON	93E	PL B311 391	+Akers, Alexander+	(OPAL Collab.)
ACTON	93F	ZPHY C58 405	+Alexander, Allison+	(OPAL Collab.)
ACTON	93K	ZPHY C60 19	+Akers, Alexander+	(OPAL Collab.)

ADRIANI	93	PL B301 136	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93E	PL B307 237	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93F	PL B309 451	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93I	PL B316 427	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93J	PL B317 467	+Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
AKERS	93B	ZPHY C60 199	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	93D	ZPHY C60 601	+Alexander, Allison+	(OPAL Collab.)
BUSKULIC	93J	ZPHY C60 71	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	93L	PL B313 520	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	93N	PL B313 549	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	93P	ZPHY C59 369	+Decamp, Goy+	(ALEPH Collab.)
NOVIKOV	93C	PL B298 453	+Okun, Vysotsky	(ITEP)
ABREU	92	ZPHY C53 567	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92G	PL B275 231	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92H	PL B276 536	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92I	PL B277 371	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92K	PL B281 383	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92M	PL B289 199	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	92N	ZPHY C55 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	92O	PL B295 383	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	92B	ZPHY C53 539	+Alexander, Allisson, Allport+	(OPAL Collab.)
ACTON	92J	PL B291 503	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92L	PL B294 436	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92N	PL B295 357	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ACTON	92O	ZPHY C56 521	+Alexander, Allison+	(OPAL Collab.)
ADEVA	92	PL B275 209	+Adriani, Aguilar-Benitez+	(L3 Collab.)
ADRIANI	92B	PL B288 404	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ADRIANI	92D	PL B292 454	+Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
ADRIANI	92E	PL B292 463	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BUSKULIC	92D	PL B292 210	+Decamp, Goy, Lees+	(ALEPH Collab.)
BUSKULIC	92E	PL B294 145	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	92B	ZPHY C53 1	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
ABE	91E	PRL 67 1502	+Amidei, Apollinari+	(CDF Collab.)
ABREU	91H	ZPHY C50 185	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	91B	PL B273 338	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
ADEVA	91I	PL B259 199	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	91B	PL B259 377	+Deschizeaux, Goy+	(ALEPH Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
DECAMP	91K	PL B273 181	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
JACOBSEN	91	PRL 67 3347	+Koetke, Adolphsen, Fujino+	(Mark II Collab.)
SHIMONAKA	91	PL B268 457	+Fujii, Miyamoto+	(TOPAZ Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	90	PRL 64 1334	+Adolphsen, Averill, Ballam+	(Mark II Collab.)
ADACHI	90F	PL B234 525	+Doser, Enomoto, Fujii+	(TOPAZ Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
BEHREND	90D	ZPHY C47 333	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
BRAUNSCH...	90	ZPHY C48 433	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ELSEN	90	ZPHY C46 349	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
HEGNER	90	ZPHY C46 547	+Naroska, Schroth, Allison+	(JADE Collab.)
KRAL	90	PRL 64 1211	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
STUART	90	PRL 64 983	+Breedon, Kim, Ko, Lander, Maeshima+	(AMY Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89C	PRL 63 720	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	89L	PL B232 425	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	89B	PRL 63 2173	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ABRAMS	89D	PRL 63 2780	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BACALA	89	PL B218 112	+Malchow, Sparks, Imlay, Kirk+	(AMY Collab.)
BAND	89	PL B218 369	+Camporesi, Chadwick, Delfino, Desangro+	(MAC Collab.)
GREENSHAW	89	ZPHY C42 1	+Warming, Allison, Ambrus, Barlow+	(JADE Collab.)
OULD-SAADA	89	ZPHY C44 567	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
SAGAWA	89	PRL 63 2341	+Lim, Abe, Fujii, Higashi+	(AMY Collab.)
ADACHI	88C	PL B208 319	+Aihara, Dijkstra, Enomoto, Fujii+	(TOPAZ Collab.)
ADEVA	88	PR D38 2665	+Anderhub, Ansari, Becker+	(Mark-J Collab.)
BRAUNSCH...	88D	ZPHY C40 163	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
BEHREND	87C	PL B191 209	+Buerger, Criegee, Dainton+	(CELLO Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
Also	85B	ZPHY C26 507	Bartel, Becker, Bowdery, Cords+	(JADE Collab.)
Also	82	PL 108B 140	Bartel, Cords, Dittmann, Eichler+	(JADE Collab.)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85F	PL 161B 188	+Becker, Cords, Felst+	(JADE Collab.)
DERRICK	85	PR D31 2352	+Fernandez, Fries, Hyman+	(HRS Collab.)
FERNANDEZ	85	PRL 54 1624	+Ford, Qi, Read+	(MAC Collab.)
LEVI	83	PRL 51 1941	+Blocker, Strait+	(Mark II Collab.)
BEHREND	82	PL 114B 282	+Chen, Fenner, Field+	(CELLO Collab.)
BRANDELIK	82C	PL 110B 173	+Braunschweig, Gather	(TASSO Collab.)

Higgs Bosons — H^0 and $H^{\pm}$, Searches for

THE HIGGS BOSON

Revised October 1997 by I. Hinchliffe (LBNL).

The Standard Model [1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2) × U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. The branching ratio of the Higgs boson into various final states is shown in Fig. 1.

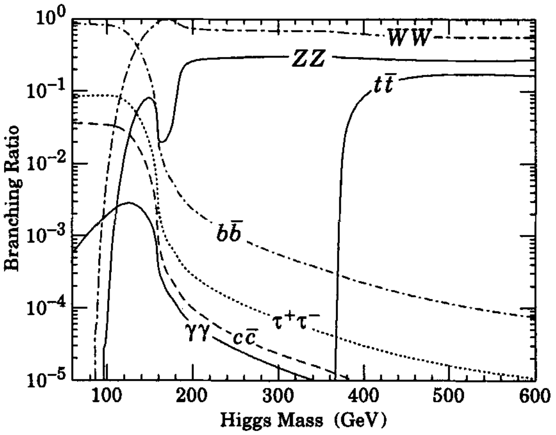


Figure 1: The branching ratio of the Higgs boson into $\gamma\gamma$, $\tau\overline{\tau}$, $b\overline{b}$, $t\overline{t}$, $c\overline{c}$, ZZ, and WW as a function of the Higgs mass. For ZZ and WW, if $M_H < 2M_Z$ (or $M_H < 2M_W$), the value indicated is the rate to ZZ^* (or WW^*) where Z^* (W^*) denotes a virtual Z (W). The $c\overline{c}$ rate depends sensitively on the poorly-determined charmed quark mass.

The Higgs coupling to stable matter is very small while its coupling to the top quark and to W and Z bosons is substantial. Hence its production is often characterized by a low rate and a poor signal to background ratio. A notable exception would be its production in the decay of the Z boson (for example $Z \to Hq\overline{q}$). Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV [2]. While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass (for $M_H > 2M_Z$) and that a boson of mass 1 TeV has a width of 500 GeV.

A scalar field theory of the type that is used to describe Higgs self-interactions can only be an effective theory (valid over a limited range of energies) if the Higgs self-coupling and hence the Higgs mass is finite. An upper bound on the Higgs mass can then be determined by requiring that the coupling has a finite value at all scales up to the Higgs mass [3]. Nonperturbative calculations using lattice [4] gauge theory that compute at arbitrary values of the Higgs coupling indicate that $M_H \lesssim 770$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory [5]. A theoretical constraint can then be obtained from the requirement that our universe is in the true minimum of the Higgs potential [6]. The constraint depends upon the top quark mass and upon the scale (Λ) up to which the Standard Model remains valid. This scale must be at least 1 TeV, resulting in the constraint [7] $M_H > 52$ GeV + 0.64 ($M_{\rm top}$-175 GeV). This constraint is weaker than that from the failure to directly observe the Higgs boson. The bound increases monotonically with the scale, for $\Lambda = 10^{19}$ GeV, $M_H > 135$ GeV + 1.9 ($M_{\rm top}$-175 GeV) − 680 ($\alpha_s(M_Z) - 0.117$). This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age [8,9]. For $\Lambda = 1$ TeV there is no meaningful constraint; and for $\Lambda = 10^{19}$ GeV $M_H > 130$ GeV + 2.3 ($M_{\rm top}$ − 175 GeV) − 815($\alpha_s(M_Z) - 0.117$) [10].

Experiments at LEP are able to exclude a large range of Higgs masses. They search for the decay $Z \to HZ^*$ or $e^+e^- \to ZH$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (*i.e.*, missing energy) or hadrons. The experimental searches have considered both $H \to$ hadrons and $H \to \tau^+\tau^-$. The best limits are shown in the Particle Listings below.

Precision measurement of electroweak parameters such as M_W, $M_{\rm top}$, and the various asymmetries at LEP and SLC are sensitive enough that they can constrain the Higgs mass through its effect in radiative corrections. The current unpublished limit is $M_H < 450$ GeV, at 95% CL with a central value of $M_H = 127^{+127}_{-72}$ GeV [11]. See also the article in this *Review* on the "Electroweak Model and Constraints on New Physics."

The process $e^+e^- \to ZH$ [12] should enable neutral Higgs bosons of masses up to 95 GeV to be discovered at LEP at a center-of-mass energy of 190 GeV [13]. The current unpublished limits corresponding to the failure to observe this process at LEP imply $M_H > 77.5$ GeV at 95% CL [14]. If the Higgs is too heavy to be observed at LEP, there is a possibility that it could be observed at the Tevatron via the processes $p\overline{p} \to HZX$ [15] and $p\overline{p} \to WHX$ [16]. Failing this, its discovery will have to wait until experiments at the LHC. If the neutral Higgs boson has mass greater than $2M_Z$, it will likely be discovered via its decay to ZZ and the subsequent decay of the Z's to charged leptons (electrons or muons) or of one Z to charged leptons and the other to neutrinos. A challenging region is that between the ultimate limit of LEP and $2M_Z$. At the upper end of this range the decay to a real and a virtual Z, followed by the decay to charged leptons is available. The decay rate of the Higgs boson into this channel falls rapidly as M_H is reduced and becomes too small for $M_H \lesssim 140$ GeV. For masses below this, the decays $H \to \gamma\gamma$ and possibly $H \to b\overline{b}$ [17] are expected to be used. The former has a small branching ratio and large background, the latter has a large branching ratio, larger background and a final state that is difficult to fully reconstruct [18].

Extensions of the Standard Model, such as those based on supersymmetry [19], can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^\pm$), two neutral scalars (H^0_1, H^0_2),* and one pseudoscalar (A) [20]. See also the articles in this *Review* on Supersymmetry.

In the simplest version of the supersymmetric model (see the *Reviews* on Supersymmetry), the mass of the lightest of these scalars depends upon the top quark mass, the ratio v_2/v_1 ($\equiv \tan\beta$), and the masses of the other supersymmetric particles. For $M_{\rm top} = 174$ GeV, there is a bound $M_{H^0_1} \lesssim 130$ GeV [21,22] at large $\tan\beta$. The bound reduces as $\tan\beta$ is lowered.

The H^0_1, H^0_2, and A couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the Standard Model. As the masses of H^0_2 and A increase, the mass of H^0_1 approaches the bound, and the properties of this lightest state become indistinguishable from those a Standard Model Higgs boson of the same mass. This observation is important since the discovery of a single Higgs boson at LEP with Standard Model couplings would not be evidence either for or against the minimal supersymmetric model. However the failure to find a Higgs boson of mass less than 130 GeV would be definite evidence against the minimal supersymmetric Standard Model. In more complicated supersymmetric models, there is always a Higgs boson of mass less than 160 GeV.

Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. Production processes that are exploited are $e^+e^- \to ZH^0_1$ and $e^+e^- \to AH^0_1$. No signal is seen; the mass limits are (weakly) dependent upon the masses of other supersymmetric particles and upon $\tan\beta$. Currently $M_{H^0_1}, M_A > 62$ GeV. See the Particle Listings below on H^0_1, Mass Limits in Supersymmetric Models.

Charged Higgs bosons can be pair-produced in e^+e^- annihilation. Searches for charged Higgs bosons depend on the assumed branching fractions to $\nu\tau$, $c\overline{s}$, and $c\overline{b}$. Data from LEP now exclude charged Higgs bosons of mass less than 54.5 GeV [23]. See the Particle Listings for details of the $H^\pm$ Mass Limit.

A charged Higgs boson could also be produced in the decay of a top quark, $t \to H^+b$. A search at CDF excludes $M_{H^+} < 147$ GeV for $\tan\beta > 100$ where the branching ratio $H^+ \to \tau\nu$ is large and at $\tan\beta < 1$ where the BR($t \to H^+b$) is large [24]. The region at intermediate values of $\tan\beta$ will be probed as the number of produced top quarks increases. Searches for these non-standard Higgs bosons will be continued at LEP [13] and at LHC [25]

Notes and References

*H^0_1 and H^0_2 are usually called h and H in the literature.

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H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. Limits that depend on the $Ht\overline{t}$ coupling may also apply to a Higgs boson of an extended Higgs sector whose couplings to up-type quarks are comparable to or larger than those of the standard one-doublet model H^0 couplings.

For comprehensive reviews, see Gunion, Haber, Kane, and Dawson, "The Higgs Hunter's Guide," (Addison-Wesley, Menlo Park, CA, 1990) and R.N. Cahn, Reports on Progress in Physics **52** 389 (1989). For a review of theoretical bounds on the Higgs mass, see M. Sher, Physics Reports (Physics Letters C) **179** 273 (1989).

Limits from Coupling to $Z/W^{\pm}$

'OUR LIMIT' is taken from the LEP Higgs Boson Searches Working group (BOCK 97), where the combination of the results of ACCIARRI 97O, BARATE 97O, ACKERSTAFF 98H, and ABREU 98E was performed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>77.5	**(CL = 95%) OUR LIMIT**			
>66.2	95	[1] ABREU 98E	DLPH	$e^+e^- \rightarrow ZH^0$
>69.4	95	[1] ACKERSTAFF 98H	OPAL	$e^+e^- \rightarrow ZH^0$
>69.5	95	[1] ACCIARRI 97O	L3	$e^+e^- \rightarrow ZH^0$
>70.7	95	[1] BARATE 97O	ALEP	$e^+e^- \rightarrow ZH^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[2] ABE 97W	CDF	$p\overline{p} \rightarrow WH^0$
>65.0	95	[3] ACKERSTAFF 97E	OPAL	$e^+e^- \rightarrow ZH^0$
>59.6	95	[4] ALEXANDER 97	OPAL	$Z \rightarrow H^0Z^*$
>60.2	95	[5] ACCIARRI 96I	L3	$Z \rightarrow H^0Z^*$
		[6] ACCIARRI 96J	L3	$Z \rightarrow H^0\gamma$
		[7] ALEXANDER 96H	OPAL	$Z \rightarrow H^0\gamma$
>60.6	95	[8] ALEXANDER 96L	OPAL	$Z \rightarrow H^0Z^*$
>63.9	95	[9] BUSKULIC 96R	ALEP	$Z \rightarrow H^0Z^*$
>55.7	95	[10] ABREU 94G	DLPH	$Z \rightarrow H^0Z^*$
>56.9	95	[11] AKERS 94B	OPAL	$Z \rightarrow H^0Z^*$
>57.7	95	[12] ADRIANI 93C	L3	$Z \rightarrow H^0Z^*$
>58.4	95	[13] BUSKULIC 93H	ALEP	$Z \rightarrow H^0Z^*$
>60	95	[14] GROSS 93	RVUE	$Z \rightarrow H^0Z^*$
		[15] ABREU 92D	DLPH	$Z \rightarrow H^0\gamma$
>38	95	[16] ABREU 92J	DLPH	$Z \rightarrow H^0Z^*$
>52	95	[17] ADEVA 92B	L3	$Z \rightarrow H^0Z^*$
		[18] ADRIANI 92F	L3	$Z \rightarrow H^0\gamma$
>48	95	[19] DECAMP 92	ALEP	$Z \rightarrow H^0Z^*$
> 0.21	99	[20] ABREU 91B	DLPH	$Z \rightarrow H^0Z^*$
>11.3	95	[21] ACTON 91	OPAL	$H^0 \rightarrow$ anything
>41.8	95	[22] ADEVA 91	L3	$Z \rightarrow H^0Z^*$
		[23] ADEVA 91D	L3	$Z \rightarrow H^0\gamma$
none 3–44	95	[24] AKRAWY 91	OPAL	$Z \rightarrow H^0Z^*$
none 3–25.3	95	[25] AKRAWY 91C	OPAL	$Z \rightarrow H^0Z^*$
none 0.21–0.818	90	[26] ABE 90E	CDF	$p\overline{p} \rightarrow (W^{\pm},Z) + H^0 + X$
none 0.846–0.987	90	[26] ABE 90E	CDF	$p\overline{p} \rightarrow (W^{\pm},Z) + H^0 + X$
none 0.21–14	95	[27] ABREU 90C	DLPH	$Z \rightarrow H^0Z^*$
none 2–32	95	[28] ADEVA 90H	L3	$Z \rightarrow H^0Z^*$
> 2	99	[29] ADEVA 90N	L3	$Z \rightarrow H^0Z^*$
none 3.0–19.3	95	[30] AKRAWY 90C	OPAL	$Z \rightarrow H^0Z^*$
> 0.21	95	[31] AKRAWY 90P	OPAL	$Z \rightarrow H^0Z^*$
none 0.032–15	95	[32] DECAMP 90	ALEP	$Z \rightarrow H^0Z^*$
none 11–24	95	[33] DECAMP 90H	ALEP	$Z \rightarrow H^0Z^*$
> 0.057	95	[34] DECAMP 90M	ALEP	$Z \rightarrow H^0ee$, $H^0\mu\mu$
none 11–41.6	95	[35] DECAMP 90N	ALEP	$Z \rightarrow H^0Z^*$

[1] Search for $e^+e^- \rightarrow ZH^0$ at E_{cm} = 161, 170, and 172 GeV in the final states $H^0 \rightarrow q\overline{q}$ with $Z \rightarrow \ell^+\ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \rightarrow \tau^+\tau^-$ with $Z \rightarrow \ell^+\ell^-$ and $q\overline{q}$. The limits also includes the data from Z decay by each experiment.

[2] ABE 97W search for associated WH^0 production in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV with $W \rightarrow \ell\nu_\ell$, $H^0 \rightarrow b\overline{b}$ and find the cross-section limit $\sigma \cdot B(H^0 \rightarrow b\overline{b}) <$(14–19) pb (95% CL) for m_H = 70–120 GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

[3] ACKERSTAFF 97E searched for $e^+e^- \rightarrow ZH^0$ at E_{cm} = 161 GeV for the final states $(q\overline{q})(b\overline{b})$, $(\nu\overline{\nu})(q\overline{q})$, $(\tau^+\tau^-)(q\overline{q})$, $(q\overline{q})(\tau^+\tau^-)$, $(e^+e^-)(q\overline{q})$, and $(\mu^+\mu^-)(q\overline{q})$ [the Z (H^0) decay products are in the first (second) parentheses]. The limit includes the results of ALEXANDER 97. Two additional low-mass candidate events are seen, consistent with expected backgrounds.

[4] ALEXANDER 97 complements the study in ALEXANDER 96L with the inclusion of the search for $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-)$, with $H^0 \rightarrow q\overline{q}$. One additional candidate event is found in the $\mu\mu$ channel, consistent with expected backgrounds.

[5] ACCIARRI 96I searched for $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. Two $e^+e^-H^0$ candidate events with large recoiling mass (above 30 GeV) were found consistent with the background expectations.

[6] ACCIARRI 96J give $B(Z \rightarrow H^0\gamma) \times B(H^0 \rightarrow q\overline{q}) < 6.9\text{–}22.9 \times 10^{-6}$ (95%CL) for $20 < m_{H^0} < 80$ GeV.

[7] ALEXANDER 96H give $B(Z \rightarrow H^0\gamma) \times B(H^0 \rightarrow q\overline{q}) < 1\text{–}4 \times 10^{-5}$ (95%CL) and $B(Z \rightarrow H^0\gamma) \times B(H^0 \rightarrow b\overline{b}) < 0.7\text{–}2 \times 10^{-5}$ (95%CL) in the range $20 < m_{H^0} < 80$ GeV.

[8] ALEXANDER 96L searched for final states with monojets or acoplanar dijets. Two observed candidate events are consistent with expected backgrounds.

[9] BUSKULIC 96R searched for $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. Three candidate events in the $\mu\mu$ channel are consistent with expected backgrounds.

[10] ABREU 94G searched for $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. Four $\ell^+\ell^-$ candidates were found (all yielding low mass) consistent with expected backgrounds.

[11] AKERS 94B searched for $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. One $\nu\overline{\nu}$ and one $\mu^+\mu^-$ candidate were found consistent with expected backgrounds.

[12] ADRIANI 93C searched for $Z \rightarrow H^0 + (\nu\overline{\nu}, e^+e^-, \mu^+\mu^-)$ with H^0 decaying hadronically or to $\tau\overline{\tau}$. Two e^+e^- and one $\mu^+\mu^-$ candidates are found consistent with expected background.

[13] BUSKULIC 93H searched for $Z \rightarrow H^0\nu\overline{\nu}$ (acoplanar jets) and $Z \rightarrow H^0 + (e^+e^-, \mu^+\mu^-)$ (lepton pairs in hadronic events).

[14] GROSS 93 combine data taken by four LEP experiments through 1991.

[15] ABREU 92D give $\sigma(e^+e^- \rightarrow Z \rightarrow H^0\gamma)\cdot\mathrm{B}(H^0 \rightarrow \text{hadrons}) <8$ pb (95% CL) for $m_{H^0} <75$ GeV and $E_\gamma >8$ GeV.

[16] ABREU 92J searched for $Z \rightarrow H^0 + (ee, \mu\mu, \tau\tau, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. Only one candidate was found, in the channel ee + 2jets, with a dijet mass 35.4 ± 5 GeV/c^2, consistent with the expected background of 1.0 ± 0.2 events in the 3 channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and of 2.8 ± 1.3 events in all 4 channels. This paper excludes 12–38 GeV. The range 0–12 GeV is eliminated by combining with the analyses of ABREU 90C and ABREU 91B.

[17] ADEVA 92B searched for $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \rightarrow$ anything, $Z \rightarrow H^0 + \tau\tau$ with $H^0 \rightarrow q\overline{q}$, and $Z \rightarrow H^0 + q\overline{q}$ with $H^0 \rightarrow \tau\tau$. The analysis excludes the range $30 < m_{H^0} < 52$ GeV.

[18] ADRIANI 92F give $\sigma(e^+e^- \rightarrow Z \rightarrow H^0\gamma)\cdot\mathrm{B}(H^0 \rightarrow \text{hadrons}) <$(2–10) pb (95% CL) for $m_{X^0} = 25$–85 GeV. Using $\sigma(e^+e^- \rightarrow Z) = 30$ nb, we obtain $\mathrm{B}(Z \rightarrow H^0\gamma)\mathrm{B}(H^0 \rightarrow \text{hadrons}) <(0.7\text{–}3) \times 10^{-4}$ (95% CL).

[19] DECAMP 92 searched for most possible final states for $Z \rightarrow H^0Z^*$.

[20] ABREU 91B searched for $Z \rightarrow H^0 + \ell\overline{\ell}$ with missing H^0 and $Z \rightarrow H^0 + (\nu\overline{\nu}, \ell\overline{\ell}, q\overline{q})$ with $H^0 \rightarrow ee$.

[21] ACTON 91 searched for $e^+e^- \rightarrow Z^*H^0$ where $Z^* \rightarrow e^+e^-, \mu^+\mu^-$, or $\nu\overline{\nu}$ and $H^0 \rightarrow$ anything. Without assuming the minimal Standard Model mass-lifetime relationship, the limit is $m_{H^0} > 9.5$ GeV.

[22] ADEVA 91 searched for $Z \rightarrow H^0 + (\mu\mu, ee, \nu\overline{\nu})$. This paper only excludes $15 < m_{H^0} < 41.8$ GeV. The 0–15 GeV range is excluded by combining with the analyses of previous L3 papers.

[23] ADEVA 91D obtain a limit $\mathrm{B}(Z \rightarrow H^0\gamma)\cdot\mathrm{B}(H^0 \rightarrow \text{hadrons}) < 4.7 \times 10^{-4}$ (95%CL) for $m_{H^0} = 30$–86 GeV. The limit is not sensitive enough to exclude a standard H^0.

[24] AKRAWY 91 searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \rightarrow q\overline{q}, \tau\tau$, and $Z \rightarrow H^0q\overline{q}$ with $H^0 \rightarrow \tau\tau$.

[25] AKRAWY 91C searched the decay channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ with $H^0 \rightarrow q\overline{q}$.

[26] ABE 90E looked for associated production of H^0 with $W^\pm$ or Z in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Searched for H^0 decays into $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^-. Most of the excluded region is also excluded at 95% CL.

[27] ABREU 90C searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ and $H^0 + q\overline{q}$ for $m_H < 1$ GeV.

[28] ADEVA 90H searched for $Z \rightarrow H^0 + (\mu\mu, ee, \nu\overline{\nu})$.

[29] ADEVA 90N looked for $Z \rightarrow H^0 + (ee, \mu\mu)$ with missing H^0 and with $H^0 \rightarrow ee, \mu\mu, \pi^+\pi^-, K^+K^-$.

[30] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \rightarrow H^0\nu\overline{\nu}$ with $H^0 \rightarrow \tau\overline{\tau}$ or $q\overline{q}$ provides the most powerful search means, but the quoted results sum all channels.

[31] AKRAWY 90P looked for $Z \rightarrow H^0 + (ee, \mu\mu)$ (H^0 missing) and $Z \rightarrow H^0\nu\overline{\nu}$, $H^0 \rightarrow e^+e^-, \gamma\gamma$.

[32] DECAMP 90 limits based on 11,550 Z events. They searched for $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau, q\overline{q})$. The decay $Z \rightarrow H^0\nu\overline{\nu}$ provides the most powerful search means, but the quoted results sum all channels. Different analysis methods are used for $m_{H^0} < 2m_\mu$ where Higgs would be long-lived. The 99% confidence limits exclude $m_{H^0} = 0.040$–12 GeV.

[33] DECAMP 90H limits based on 25,000 $Z \rightarrow$ hadron events.

[34] DECAMP 90M looked for $Z \rightarrow H^0\ell\ell$, where H^0 decays outside the detector.

[35] DECAMP 90N searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \rightarrow$ (hadrons, $\tau\tau$).

H^0 Indirect Mass Limits from Electroweak Analysis

For limits obtained before the direct measurement of the top quark mass, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review. For indirect limits obtained from other considerations of theoretical nature, see the review on "The Higgs boson."

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[36] CHANOWITZ	98	RVUE	
$141^{+140}_{-\ 77}$		[37] DEBOER	97B	RVUE	
$127^{+143}_{-\ 71}$		[38] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
$158^{+148}_{-\ 84}$		[39] DITTMAIER	97	RVUE	
$149^{+148}_{-\ 82}$		[40] RENTON	97	RVUE	
$\lesssim 550$	90	[41] DITTMAIER	96	RVUE	
$145^{+164}_{-\ 77}$		[42] ELLIS	96C	RVUE	
185^{+251}_{-134}		[43] GURTU	96	RVUE	
$63^{+\ 97}_{-\ \ 0}$		[44] CHANKOWSKI	95	RVUE	
<730	95	[45] ERLER	95	RVUE	
<740	95	[46] MATSUMOTO	95	RVUE	
$45^{+\ 95}_{-\ 28}$		[47] ELLIS	94B	RVUE	
$69^{+188}_{-\ \ 9}$		[48] GURTU	94	RVUE	
		[49] MONTAGNA	94	RVUE	

[36] CHANOWITZ 98 fits LEP and SLD Z-decay-asymmetry data (as reported in ABBANEO 97), and explores the sensitivity of the fit to the weight ascribed to measurements that are individually in significant contradiction with the direct-search limits. Various prescriptions are discussed, and significant variations of the 95%CL Higgs-mass upper limits are found. The Higgs-mass central value varies from 100 to 250 GeV and the 95%CL upper limit from 340 GeV to the TeV scale.

[37] DEBOER 97B fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from CDF/DØ and CLEO $b \rightarrow s\gamma$ data (ALAM 95). $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[38] DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta^{\text{lept}}_{\text{eff}}$ as a function of m_H, using $\sin^2\theta^{\text{lept}}_{\text{eff}}$ 0.23165(24) as reported in ALCARAZ 96, $m_t = 175 \pm 6$ GeV, and $\Delta\alpha_{\text{had}} = 0.0280(9)$.

[39] DITTMAIER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with $m_t = 175 \pm 6$ GeV, $1/\alpha(m^2_Z) = 128.89 \pm 0.09$. Exclusion of the SLD data gives $m_H = 261^{+224}_{-128}$ GeV. Taking only the data on m_t, m_W, $\sin^2\theta^{\text{lept}}_{\text{eff}}$, and Γ^{lept}_Z, the authors get $m_H = 190^{+174}_{-102}$ GeV and $m_H = 296^{+243}_{-143}$ GeV, with and without SLD data, respectively. The 95% CL upper limit is given by 550 GeV (800 GeV removing the SLD data).

[40] RENTON 97 fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from $p\overline{p}$, and low-energy νN data available in early 1997. $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[41] DITTMAIER 96 fit to m_W, LEP, and SLD data available in the Summer of 1995 (with and without m_t=180 ± 12 GeV from CDF/DØ), leaving out R_b and R_c. They argue that the low Higgs mass obtained in some electroweak analyses is an artifact of including the observed value of R_b, which is incompatible with the rest of the data. Exclusion of the SLD data pushes the 90%CL limit on m_{H^0} above 1 TeV.

[42] ELLIS 96C fit to LEP, SLD, m_W, neutral-current data available in the summer of 1996, plus $m_t = 175 \pm 6$ GeV from CDF/DØ . The fit yields $m_t = 172 \pm 6$ GeV.

[43] GURTU 96 studies the effect of the mutually incompatible SLD and LEP asymmetry data on the determination of m_H. Use is made of data available in the Summer of 1996. The quoted value is obtained by increasing the errors *à la* PDG. A fit ignoring the SLD data yields 267^{+242}_{-135} GeV.

[44] CHANKOWSKI 95 fit to LEP, SLD, and W mass data available in the spring of 1995 plus $m_t = 176 \pm 13$ GeV. Exclusion of the SLD data increases the mass to $m_H = 121^{+207}_{-\ 58}$ GeV (m_H <800 GeV at 95% CL).

[45] ERLER 95 fit to LEP, SLC, W mass, and various low-energy data available in the summer of 1994 plus m_t=174 ± 16 GeV from CDF. The limit without m_t is 880 GeV. However, the preference for lighter m_H is due to R_b and A_{LR}, both of which do not agree well with the Standard Model prediction.

[46] MATSUMOTO 95 fit to LEP, SLD, W mass, and various neutral current data available in the summer of 1994 plus m_t=180 ± 13 GeV from CDF/DØ , and the LEP direct limit m_H >63 GeV. $\alpha_s(m_Z) = 0.124$ is used. Fixing $\alpha_s(m_Z) = 0.116$ lowers the upper limit to 440 GeV. Dependence on $\alpha(m_Z)$ is given in the paper.

[47] ELLIS 94B fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 plus $m_t = 167 \pm 12$ GeV determined from CDF/DØ $t\overline{t}$ direct searches. $\alpha_s(m_Z) = 0.118 \pm 0.007$ is used. The fit yields $m_t = 162 \pm 9$ GeV. A fit without the SLD data gives $m_H = 130^{+320}_{-\ 90}$ GeV.

[48] GURTU 94 fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 as well as $m_t = 174 \pm 16$ GeV. A fit without $\Gamma(Z \rightarrow b\overline{b})/\Gamma(Z \rightarrow \text{hadrons})$ gives $m_H = 120^{+364}_{-\ 60}$ GeV.

[49] MONTAGNA 94 fit to LEP and SLD, W-mass data together with $m_t = 174 \pm 17$ GeV. Although the data favor smaller Higgs masses, the authors do not regard it significant.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

The parameter x denotes the Higgs coupling to charge −1/3 quarks and charged leptons relative to the value in the standard one-Higgs-doublet model.

In order to prevent flavor-changing neutral currents in models with more than one Higgs doublet, only one of the Higgs doublets can couple to quarks of charge 2/3. The same requirement applies independently to charge −1/3 quarks and to leptons. Higgs couplings can be enhanced or suppressed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>69.6	95	[50] ACCIARRI	98B	L3	Invisible H^0
		[51] ACKERSTAFF	98B	OPAL	$e^+e^- \rightarrow H^0Z^{(*)}$, $H^0 \rightarrow \gamma\gamma$
		[52] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[53] ACCIARRI	96I	L3	$Z \rightarrow H^0Z^*$
>66.7	95	[54] ACCIARRI	96I	L3	Invisible H^0
		[55] ACCIARRI	96J	L3	$Z \rightarrow H^0Z^*$, $H^0 \rightarrow \gamma\gamma$

		[56] ALEXANDER	96H	OPAL	$Z \to H^0 Z^*$, $H^0 \to \gamma\gamma$
		[57] ABREU	95H	DLPH	$Z \to H^0 Z^*$, $H^0 A^0$
		[58] BRAHMACH...	93	RVUE	
		[59] BUSKULIC	93I	ALEP	$Z \to H^0 Z^*$
>65	95	[54] BUSKULIC	93I	ALEP	invisible H^0
		[60] LOPEZ-FERN...	93	RVUE	
		[61] ADRIANI	92G	L3	$Z \to H^0 Z^*$
		[62] PICH	92	RVUE	Very light Higgs
> 3.57	95	[63] ACTON	91	OPAL	$Z \to H^0 Z^*$
		[64] DECAMP	91F	ALEP	$Z \to H^0 \ell^+ \ell^-$
		[65] DECAMP	91I	ALEP	Z decay
> 0.21	95	[66] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
		[67] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+ e^-)$
		[68] SNYDER	89	MRK2	$B \to H^0 X$ $(H^0 \to e^+ e^-)$
none 0.6–6.2	90	[69] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=2
none 0.6–7.9	90	[69] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=4
none 3.7–5.6	90	[70] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=2
none 3.7–8.2	90	[70] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=4

[50] ACCIARRI 98B searches for $e^+ e^- \to Z H^0$ events, with $Z \to$ hadrons and H^0 decaying invisibly. The limit assumes SM production cross section, and B($Z \to$ invisible)=100%. For limits under other assumptions, see their Fig. 5b.

[51] ACKERSTAFF 98B search for associate production of a $\gamma\gamma$ resonance and a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+ \ell^-$ pair in $e^+ e^-$ annihilation at $\sqrt{s} \simeq 91$, 130–140, and 161–172 GeV. The cross-section limit $\sigma(e^+ e^- \to H^0 Z^{(*)}) \cdot B(H^0 \to \gamma\gamma) < 0.29$–0.83 pb (95%CL) is obtained for $m_H = 40$–160 GeV at $\sqrt{s} = 161$–172 GeV, $\sigma \cdot B < 0.09$ pb for $m_H = 40$–80 GeV at $\sqrt{s} \simeq 91$ GeV. See also their Fig. 9 for the limit on $\sigma(H^0) \cdot B(H^0 \to \gamma\gamma)/\sigma(H^0_{SM})$.

[52] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H^0_1 Z Z$ coupling and obtain $m_{H^0_1} \gtrsim$ 5 GeV or $m_{A^0} \gtrsim 5$ GeV for $\tan\beta > 50$. Other Higgs bosons are assumed to be much heavier.

[53] See Figs. 5 and 6 of ACCIARRI 96I for the excluded region in the $(m_{H^0}, \Gamma(Z \to Z^* H^0))$ plane (normalized to the Standard Model Higgs) for a general Higgs having a similar decay signature to Standard Model Higgs boson or decaying invisibly.

[54] These limits are for H^0 with the standard coupling to Z but decaying to weakly interacting particles.

[55] ACCIARRI 96J give B($Z \to H^0$ + hadrons)×B($H^0 \to \gamma\gamma$) < 2.3–6.9×10^{-6} for 20 $< m_{H^0} < 70$ GeV.

[56] ALEXANDER 96H give B($Z \to H^0 + q\overline{q}$)×B($H^0 \to \gamma\gamma$) $< 2 \times 10^{-6}$ in the range $40 < m_{H^0} < 80$ GeV.

[57] See Fig. 4 of ABREU 95H for the excluded region in the $m_{H^0} - m_{A^0}$ plane for general two-doublet models. For $\tan\beta > 1$, the region $m_{H^0} + m_{A^0} \lesssim 87$ GeV, $m_{H^0} < 47$ GeV is excluded at 95% CL.

[58] BRAHMACHARI 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. If H^0 coupling to Z is at least $1/\sqrt{2}$ of the Standard Model H^0, the DECAMP 92 limit of 48 GeV changes within ±6 GeV for arbitrary B($H^0 \to$ SM-like)+B($H^0 \to$ invisible)=1.

[59] See Fig. 1 of BUSKULIC 93I for the limit on $Z Z H^0$ coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson or decaying invisibly. If the decay rate for $Z \to H^0 Z^*$ is >10% of the minimal Standard Model rate, then $m_{H^0} > 40$ GeV. For the standard rate the limit is 58 GeV.

[60] LOPEZ-FERNANDEZ 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. See Fig. 2 for excluded region in m_{H^0}-ZZH coupling plane with arbitrary B($H^0 \to$ SM-like)+B($H^0 \to$ invisible)=1. $m_H > 50$ GeV is obtained if the H^0 coupling strength to the Z is greater than 0.2 times the Standard Model rate.

[61] See Fig. 1 of ADRIANI 92G for the limit on $Z Z H^0$ coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson. For most masses below 30 GeV, the rate for $Z \to H^0_1 Z^*$ is less than 10% of the Standard Model rate.

[62] PICH 92 analyse H^0 with $m_{H^0} < 2m_\mu$ in general two-doublet models. Excluded regions in the space of mass-mixing angles from LEP, beam dump, and $\pi^\pm$, η rare decays are shown in Figs. 3,4. The considered mass region is not totally excluded.

[63] ACTON 91 limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.24 (0.56) times that for the standard Higgs boson for Higgs masses below $2m_\mu$ ($2m_\tau$).

[64] DECAMP 91F search for $Z \to H^0 \ell^+ \ell^-$ where H^0 escapes before decaying. Combining this with DECAMP 90M and DECAMP 90N, they obtain B($Z \to H^0 \ell^+ \ell^-$)/B($Z \to \ell^+ \ell^-$) $< 2.5 \times 10^{-3}$ (95%CL) for $m_{H^0} < 60$ GeV.

[65] See Figs. 1, 3, 4, 5 of DECAMP 91I for excluded regions for the masses and mixing angles in general two-doublet models.

[66] AKRAWY 90P limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.57 times that for the Standard Higgs boson.

[67] DAVIER 89 give excluded region in m_{H^0}-x plane for m_{H^0} ranging from 1.2 MeV to 50 MeV.

[68] SNYDER 89 give limits on B($B \to H^0 X$)·B($H^0 \to e^+ e^-$) for $100 < m_{H^0} < 200$ MeV, $c\tau < 24$ mm.

[69] First order QCD correction included with $\alpha_s \approx 0.2$. Their figure 4 shows the limits vs. x.

[70] ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $< E(\gamma) < 4.0$ GeV with typically BR< 0.01 for $\Upsilon(1S)$ and BR< 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit B($\Upsilon(1S) \to H^0 \gamma$) $< 1.5 \times 10^{-3}$ at $E(\gamma) = 1.07$ GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m_{H^0} = m_\Upsilon (1 - 2E(\gamma)/m_\Upsilon)^{1/2}$.

H^0_1 (Higgs Boson) MASS LIMITS in Supersymmetric Models

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H^0_1 and H^0_2, where we define $m_{H^0_1} < m_{H^0_2}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^\pm$). H^0_1 and H^0_2 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H^0_1} \le m_Z$, $m_{H^0_2} \ge m_Z$, $m_{A^0} \ge m_{H^0_1}$, and $m_{H^\pm} \ge m_W$. However, as described in the "Note on Supersymmetry," recent calculations of one-loop radiative corrections show that these relations may be violated. Many experimental analyses have not taken into account these corrections; footnotes indicate when these corrections are included. The results assume no invisible H^0 or A^0 decays.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>59.5	95	[71] ABREU	98E	DLPH	$\tan\beta > 1$
>62.5	95	[72] BARATE	97P	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[73] ACCIARRI	97N	L3	
>44.3	95	[74] ALEXANDER	97	OPAL	any $\tan\beta$
>44	95	[75] ABREU	95H	DLPH	any $\tan\beta$
		[76] ROSIEK	95	RVUE	
>44.4	95	[77] ABREU	94O	DLPH	$m_{H^0_1} = m_{A^0}$, any $\tan\beta$
>44.5	95	[78] AKERS	94I	OPAL	$\tan\beta > 1$
>44	95	[79] BUSKULIC	93I	ALEP	$\tan\beta > 1$
>34	95	[80] ABREU	92J	DLPH	$\tan\beta > 0.6$
>29	95	[80] ABREU	92J	DLPH	any $\tan\beta$
>42	95	[81] ADRIANI	92G	L3	$1 < \tan\beta < 50$
> 0.21	95	[82] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[83] ABREU	91B	DLPH	any $\tan\beta$
none 3–38	95	[84] AKRAWY	91C	OPAL	$\tan\beta > 6$
none 3–22	95	[84] AKRAWY	91C	OPAL	$\tan\beta > 0.5$
		[85] BLUEMLEIN	91	BDMP	$pN \to H^0_1 X$ $(H^0_1 \to e^+ e^-, 2\gamma)$
>41	95	[86] DECAMP	91I	ALEP	$\tan\beta > 1$
> 9	95	[87] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[87] ABREU	90E	DLPH	$\tan\beta > 1$
>26	95	[88] ADEVA	90R	L3	$\tan\beta > 1$
none 0.05–3.1	95	[89] DECAMP	90E	ALEP	any $\tan\beta$
none 0.05–13	95	[89] DECAMP	90E	ALEP	$\tan\beta > 0.6$
none 0.006–20	95	[89] DECAMP	90E	ALEP	$\tan\beta > 2$
>37.1	95	[89] DECAMP	90E	ALEP	$\tan\beta > 6$
none 0.05–20	95	[90] DECAMP	90H	ALEP	$\tan\beta > 0.6$
none 0.006–21.4	95	[90] DECAMP	90H	ALEP	$\tan\beta > 2$
> 3.1	95	[91] DECAMP	90M	ALEP	any $\tan\beta$

[71] ABREU 98E search for $e^+ e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $q\overline{q}\tau^+\tau^-$ at $\sqrt{s}$ = 161–172 GeV. The results from the SM Higgs search described in the same paper are also used to set these limits. Two-loop radiative corrections are included with m_{top} = 175 GeV, M_{SUSY} = 1 TeV, and maximal scalar top mixings.

[72] BARATE 97P search for $e^+ e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at $\sqrt{s}$ = 130–172 GeV and combine with BARATE 97O limit on $e^+ e^- \to H^0_1 Z$. Two-loop radiative corrections are included with m_{top} = 175 GeV and M_{SUSY} = 1 TeV, and maximal scalar top mixings. The invisible decays $H^0_1 \to \tilde{\chi}^0 \tilde{\chi}^0$ are not allowed in the analysis, as ruled out in the relevant kinematic region by BUSKULIC 96K.

[73] ACCIARRI 97N search for $e^+ e^- \to H^0_1 A^0$ in four-jet final states at $\sqrt{s}$ = 130–172 GeV. Cross-section limits are obtained for $|m_{H^0_1} - m_{A^0}|$ = 0, 10, and 20 GeV.

[74] ALEXANDER 97 search for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$ and use Γ_Z (nonstandard) < 13.9 MeV. Radiative corrections using two-loop renormalization group equations are included with $m_t < 195$ GeV and the MSSM parameter space is widely scanned. Possible invisible decay mode $H^0_1 \to \tilde{\chi}^0 \tilde{\chi}^0$ is included in the analysis.

[75] ABREU 95H search for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$. Two-loop corrections are included with m_t=170 GeV, $m_{\tilde{t}}$=1 TeV. Including only one-loop corrections does not change the limit.

[76] ROSIEK 95 study the dependence of $m_{H^0_1}$ limit on various supersymmetry parameters. They argue that H^0_1 as light as 25 GeV is not excluded by ADRIANI 92G data in the region $m_{A^0} \sim 60$ GeV if $m_{\tilde{t}} \lesssim 200$ GeV and $\tilde{t}_L$-$\tilde{t}_R$ mixing is large.

[77] ABREU 94O study $H^0_1 A^0 \to$ four jets and combine with ABREU 94G analysis. The limit applies if the H^0_1-A^0 mass difference is <4 GeV.

[78] AKERS 94I search for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$. One-loop corrections are included with m_t <200 GeV, $m_{\tilde{t}}$ <1 TeV. See Fig. 10 for limits for $\tan\beta < 1$.

[79] BUSKULIC 93I search for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$. One-loop corrections are included with any m_t, $m_{\tilde{t}} > m_t$.

[80] ABREU 92J searched for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$ with $H^0_1, A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[81] ADRIANI 92G search for $Z \to H^0_1 Z^*$, $Z \to H^0_1 A^0 \to 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \to A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections to the Higgs potential are included with $90 < m_t < 250$ GeV, $m_t < m_{\tilde{t}} < 1$ TeV.

[82] ABREU 91B result is based on negative search for $Z \to H^0_1 f\overline{f}$ and the limit on invisible Z width $\Gamma(Z \to H^0_1 A^0) <$ 39 MeV (95%CL), assuming $m_{A^0} < m_{H^0_1}$.

[83] ABREU 91B result obtained by combining with analysis of ABREU 90I.

[84] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- JJ$ or 4τ and $Z \to H_1^0 Z^*$ ($H_1^0 \to q\overline{q}$, $Z^* \to \nu\overline{\nu}$ or e^+e^- or $\mu^+\mu^-$). See paper for the excluded region for the case $\tan\beta < 1$. Although these limits do not take into account the one-loop radiative corrections, the authors have reported unpublished results including these corrections and showed that the excluded region becomes larger.

[85] BLUEMLEIN 91 excluded certain range of $\tan\beta$ for $m_{H_1^0} < 120$ MeV, $m_{A^0} < 80$ MeV.

[86] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau JJ$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses.

[87] ABREU 90E searched for $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. $m_{H_1^0} < 210$ MeV is not excluded by this analysis.

[88] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau JJ$ or 4τ and $Z \to H_1^0 Z^*$. Some region of $m_{H_1^0} < 4$ GeV is not excluded by this analysis.

[89] DECAMP 90E look for $Z \to H_1^0 A^0$ as well as $Z \to H_1^0 \ell^+\ell^-$, $Z \to H_1^0 \nu\overline{\nu}$ with 18610 Z decays. Their search includes signatures in which H_1^0 and A^0 decay to $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, or $q\overline{q}$. See their figures of $m_{H_1^0}$ vs. $\tan\beta$.

[90] DECAMP 90H is similar to DECAMP 90E but with 25,000 Z decays.

[91] DECAMP 90M looked for $Z \to H^0 \ell\ell$, where H_1^0 decays outside the detector. This excludes a region in the ($m_{H_1^0}$, $\tan\beta$) plane centered at $m_{H_1^0} = 50$ MeV, $\tan\beta = 0.5$. This limit together with DECAMP 90E result excludes $m_{H_1^0} < 3$ GeV for any $\tan\beta$.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

Limits on the A^0 mass from e^+e^- collisions arise from direct searches in the $e^+e^- \to A^0 H_1^0$ channel and indirectly from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the "Note on Supersymmetry," at the one-loop level and in the simplest cases, these relations depend on the masses of the t quark and $\tilde{t}$ squarks. The limits are weaker for larger t and $\tilde{t}$ masses, while they increase with the inclusion of two-loop radiative corrections. Some specific examples of these dependences are provided in the footnotes to the listed papers.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>51.0	95	[92] ABREU	98E	DLPH	$\tan\beta > 1$
>62.5	95	[93] BARATE	97P	ALEP	$\tan\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[94] ACCIARRI	97N	L3	
>23.5	95	[95] ALEXANDER	97	OPAL	$\tan\beta > 1$, $m_t < 195$ GeV
>60	95	[96] KEITH	97	RVUE	$\tan\beta < 1$
>27	95	[97] ABREU	95H	DLPH	$\tan\beta > 1$, $m_t = 170$ GeV
>44.4	95	[98] ABREU	94O	DLPH	$m_{H_1^0} = m_{A^0}$, any $\tan\beta$
>24.3	95	[99] AKERS	94I	OPAL	$\tan\beta > 1$, $m_t < 200$ GeV
>44.5	95	[99] AKERS	94I	OPAL	$\tan\beta > 1$, $m_{H_1^0} = m_{A^0}$
>21	95	[100] BUSKULIC	93I	ALEP	$\tan\beta > 1$, $m_t = 140$ GeV
		[101] ELLIS	93	RVUE	Electroweak
>34	95	[102] ABREU	92J	DLPH	$\tan\beta > 3$
>22	95	[103] ADRIANI	92G	L3	$1 < \tan\beta < 50$, $m_t < 250$ GeV
> 0.21	95	[104] BUSKULIC	92	ALEP	$\tan\beta > 1$
none 3–40.5	95	[105] AKRAWY	91C	OPAL	$\tan\beta > 1$, if 3 GeV $< m_{H_1^0} < m_{A^0}$
>20	95	[106] DECAMP	91I	ALEP	$\tan\beta > 1$
>34	95	[107] ABREU	90E	DLPH	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$
>12	95	[107] ABREU	90E	DLPH	$\tan\beta < 1$
>39	95	[108] ADEVA	90R	L3	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$

[92] ABREU 98E search for $e^+e^- \to H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$ and $q\overline{q}\tau^+\tau^-$ at $\sqrt{s}$ = 161–172 GeV. The results from the SM Higgs search described in the same paper are also used to set these limits. Two-loop radiative corrections are included with $m_{\text{top}} =$ 175 GeV, $M_{\text{SUSY}} = 1$ TeV, and maximal scalar top mixings.

[93] BARATE 97P search for $e^+e^- \to H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at $\sqrt{s}$ = 130–172 GeV and combine with BARATE 97O limit on $e^+e^- \to H_1^0 Z$. Two-loop radiative corrections are included with $m_{\text{top}} = 175$ GeV and $M_{\text{SUSY}} = 1$ TeV, and maximal scalar top mixings. The invisible decays $H_1^0 \to \tilde{\chi}^0\tilde{\chi}^0$ are not allowed in the analysis, as ruled out in the relevant kinematic region by BUSKULIC 96K.

[94] ACCIARRI 97N search for $e^+e^- \to H_1^0 A^0$ in four-jet final states at $\sqrt{s}$ = 130–172 GeV. Cross-section limits are obtained for $|m_{H_1^0} - m_{A^0}|$ = 0, 10, and 20 GeV.

[95] ALEXANDER 97 search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ and use Γ_Z (nonstandard) < 13.9 MeV. Radiative corrections using two-loop renormalization group equations are included with $m_t < 195$ GeV and the MSSM parameter space is widely scanned. Possible invisible decay mode $H_1^0 \to \tilde{\chi}^0\tilde{\chi}^0$ is included in the analysis. The limit improves to 44 GeV for $\tan\beta \gtrsim 1.5$, but goes to 0 for $\tan\beta < 0.9$ and $m_t > 195$ GeV.

[96] KEITH 97 uses Tevatron data on $t\overline{t}$ production to estimate B($t \to H^+ b$)< 0.3 at 95%CL. The resulting constraints on m_{H^+} and the one-loop MSSM relation between m_{H^+} and m_{A^0} give rise to the limit shown on m_{A^0}.

[97] ABREU 95H search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with $m_t = 170$ GeV, $m_{\tilde{t}} = 1$ TeV. The limit becomes weak for larger m_t: at $m_t =$ 190 GeV, the limit is 14 GeV. The limit at $m_t = 170$ GeV would increase to 39 GeV if two-loop radiative corrections were included. m_t and $m_{\tilde{t}}$ dependences are shown in Fig. 6.

[98] ABREU 94O study $H_1^0 A^0 \to$ four jets and combine with ABREU 94G analysis. The limit applies if the H_1^0-A^0 mass difference is <4 GeV.

[99] AKERS 94I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with $m_t < 200$ GeV, $m_{\tilde{t}} < 1$ TeV. See Fig. 10 for limits for $\tan\beta < 1$.

[100] BUSKULIC 93I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections to the Higgs potential are included with any m_t, $m_{\tilde{t}} > m_t$. For $m_t = 140$ GeV and $m_{\tilde{t}} = 1$ TeV, the limit is $m_{A^0} > 45$ GeV. Assumes no invisible H^0 or A^0 decays.

[101] ELLIS 93 analyze possible constraints on the MSSM Higgs sector by electroweak precision measurements and find that m_{A^0} is not constrained by the electroweak data.

[102] ABREU 92J searched for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ with $H_1^0, A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[103] ADRIANI 92G search for $Z \to H_1^0 Z^*$, $Z \to H_1^0 A^0 \to 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \to A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections are included with $90 < m_t < 250$ GeV, $m_t < m_{\tilde{t}} < 1$ TeV. The region $m_{A^0} < 11$ GeV is allowed if $42 < m_{H_1^0} < 62$ GeV, but is excluded by other experiments.

[104] BUSKULIC 92 limit is from $\Gamma(Z)$, $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0$. The limit is valid for any $m_{H_1^0}$ below the the theoretical limit $m_{H_1^0} < 64$ GeV which holds for $m_{A^0} \sim 0$ in the minimal supersymmetric model. One-loop radiative corrections are included.

[105] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- JJ$ or 4τ. See paper for the excluded region for the case $\tan\beta < 1$.

[106] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau JJ$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses. For $m_t = 140$ GeV and $m_{\tilde{q}} = 1$ TeV, the limit is $m_{A^0} > 31$ GeV.

[107] ABREU 90E searched $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. $m_{A^0} < 210$ MeV is not excluded by this analysis.

[108] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau JJ$ or 4τ and $Z \to H_1^0 Z^*$. Some region of $m_{A^0} < 5$ GeV is not excluded by this analysis.

MASS LIMITS for Associated Higgs Production in e^+e^- Interactions

In multi-Higgs models, associated production of Higgs via virtual or real Z in e^+e^- annihilation, $e^+e^- \to H_1^0 H_2^0$, is possible if H_1^0 and H_2^0 have opposite CP eigenvalues. Limits are for the mass of the heavier Higgs H_2^0 in two-doublet models.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>53	95	[109] AKERS	94I	OPAL	$m_{H_1^0} < 12$ GeV
		[110] ADRIANI	92G	L3	
>45	95	[111] DECAMP	90H	ALEP	$m_{H_1^0} < 20$ GeV
>37.5	95	[111] DECAMP	90H	ALEP	$m_{H_1^0} < m_{H_2^0}$
none 5–45	95	[112] KOMAMIYA	90	MRK2	$m_{H_1^0} < 0.5$ GeV, $H_2^0 \to q\overline{q}$ or $\tau^+\tau^-$
> 8	90	[113] KOMAMIYA	89	MRK2	$H_1^0 \to \mu^+\mu^-$, $H_2^0 \to q\overline{q}$, $\tau^+\tau^-$
>28	95	[114] LOW	89	AMY	$m_{H_1^0} \lesssim 20$ MeV, $H_2^0 \to q\overline{q}$
none 2–9	90	[115] AKERLOF	85	HRS	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 4–10	90	[116] ASH	85C	MAC	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \to \tau^+\tau^-$, $c\overline{c}$
none 1.3–24.7	95	[115] BARTEL	85L	JADE	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \to f\overline{f}$ or $f\overline{f}H_1^0$
none 1.2–13.6	95	[115] BEHREND	85	CELL	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 1–11	90	[115] FELDMAN	85	MRK2	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 1–9	90	[115] FELDMAN	85	MRK2	$m_{H_1^0} = m_{H_2^0}$, $H_2^0 \to f\overline{f}$

[109] AKERS 94I search for $Z \to H_1^0 H_2^0$ with various decay modes. See Fig. 11 for the full excluded mass region in the general two-doublet model, from which the limit above is taken. In particular, for $m_{H_1^0} = m_{H_2^0}$ the limit becomes >38 GeV.

[110] ADRIANI 92G excluded regions of the $m_{H_1^0} - m_{A^0}$ plane for various decay modes with limits B($Z \to H_1^0 H_2^0$) <(2–20) × 10^{-4} are shown in Figs. 2–5.

[111] DECAMP 90H search for $Z \to H_1^0 e^+e^-$, $H_1^0 \mu^+\mu^-$, $H_1^0 \tau^+\tau^-$, $H_1 q\overline{q}$, low multiplicity final states, τ-τ-jet-jet final states and 4-jet final states.

[112] KOMAMIYA 90 limits valid for $\cos^2(\alpha - \beta) \approx 1$. They also search for the cases $H_1^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, and $H_2^0 \to H_1^0 H_1^0$. See their Fig. 2 for limits for these cases.

[113] KOMAMIYA 89 assume B($H_1^0 \to \mu^+\mu^-$) = 100 %, $2m_\mu < m_{H_1^0} < m_\tau$. The limit is for maximal mixing. A limit of $m_{H_2^0} > 18$ GeV for the case $H_2^0 \to H_1^0 H_1^0$ ($H_1^0 \to \mu^+\mu^-$) is also given. From PEP at $E_{\text{cm}} = 29$ GeV.

[114] LOW 89 assume that H_1^0 escapes the detector. The limit is for maximal mixing. A reduced limit of 24 GeV is obtained for the case $H_2^0 \to H_1^0 f\overline{f}$. Limits for a Higgs-triplet model are also discussed. $E_{\rm cm}^{ee}$ = 50–60.8 GeV.
[115] The limit assumes maximal mixing and that H_1^0 escapes the detector.
[116] ASH 85 assumes that H_1^0 escapes undetected. The bound applies up to a mixing suppression factor of 5.

$H^\pm$ (Charged Higgs) MASS LIMITS

Most of the following limits assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\overline{s}) = 1$. DECAMP 90I, BEHREND 87, and BARTEL 86 assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\overline{s}) + B(H^+ \to c\overline{b}) = 1$. All limits from Z decays as well as ADACHI 90B assume that H^+ has weak isospin $T_3 = +1/2$.

For limits obtained in hadronic collisions before the observation of the top quark, and based on the top mass values inconsistent with the current measurements, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review.

The limits are also applicable to pointlike techni-pions. For a discussion of techniparticles, see EICHTEN 86.

In the following tanβ is the ratio of the two vacuum expectation values in the two-doublet model.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 54.5	95	[117] ABREU 98F	DLPH	$B(\tau\nu) = 0$–1
> 52.0	95	[117] ACKERSTAFF 98I	RVUE	$B(\tau\nu) = 0$–1
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[118] ABE 97L	CDF	$t \to bH^+, H \to \tau\nu$
		[119] ACCIARRI 97F	L3	$B \to \tau\nu_\tau$
		[120] AMMAR 97B	CLEO	$\tau \to \mu\nu\nu$
		[121] COARASA 97	RVUE	$B \to \tau\nu_\tau X$
		[122] GUCHAIT 97	RVUE	$t \to bH^+, H \to \tau\nu$
		[123] MANGANO 97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[124] STAHL 97	RVUE	$\tau \to \mu\nu\nu$
		[125] ABE 96G	CDF	$t \to bH^+, H^+ \to \tau^+\nu_\tau$
> 44.1	95	[126] ALEXANDER 96I	OPAL	$B(\tau\nu) = 0$–1
>244	95	[127] ALAM 95	CLE2	$b \to s\gamma$
		[128] BUSKULIC 95	ALEP	$b \to \tau\nu_\tau X$
> 43.5	95	[129] ABREU 94O	DLPH	$B(\tau\nu) = 0$–1
		[130] BARGER 93	RVUE	$b \to s\gamma$
		[131] BELANGER 93	RVUE	$b \to s\gamma$
		[130] HEWETT 93	RVUE	$b \to s\gamma$
> 41	95	[132] ADRIANI 92G	L3	$B(\tau\nu) = 0$–1
> 41.7	95	[133,134] DECAMP 92	ALEP	$B(\tau\nu) = 0$–1
none 8.0–20.2	95	[135] YUZUKI 91	VNS	$B(\ell\nu) = 0$–1
> 29	95	[133,136] ABREU 90B	DLPH	$B(\tau\nu) = 0$–1
> 19	95	[133,137] ADACHI 90B	TOPZ	$B(\tau\nu) = 0$–1
> 36.5	95	[133,138] ADEVA 90M	L3	$B(\tau\nu) = 0$–1
> 35	95	[133,139] AKRAWY 90K	OPAL	$B(\tau\nu) = 0$–1
> 35.4	95	[133,140] DECAMP 90I	ALEP	$B(\tau\nu) = 0$–1
none 10–20	95	[141] SMITH 90B	AMY	$B(\tau\nu) > 0.7$
> 19	95	[140] BEHREND 87	CELL	$B(\tau\nu) = 0$–1
> 18	95	[142] BARTEL 86	JADE	$B(\tau\nu)$=0.1–1.0
> 17	95	[142] ADEVA 85	MRKJ	$B(\tau\nu)$=0.25–1.0

[117] Search for $e^+e^- \to H^+H^-$ at $\sqrt{s}$=130–172 GeV.
[118] ABE 97L search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at $E_{\rm cm} = 1.8$ TeV, with $H^+ \to \tau^+\nu_\tau$, τ decaying hadronically. The limits depend on the choice of the $t\overline{t}$ cross section. See Fig. 3 for the excluded region. The excluded mass region extends to over 140 GeV for tanβ values above 100.
[119] ACCIARRI 97F give a limit $m_{H^+} > 2.6$ tanβ GeV (90%CL) from their limit on the exclusive $B \to \tau\nu_\tau$ branching ratio.
[120] AMMAR 97B measure the Michel parameter ρ from $\tau \to e\nu\nu$ decays and assmes e/μ universality to extract the Michel η parameter from $\tau \to \mu\nu\nu$ decays. The measurement is translated to a lower limit on m_{H^+} in a two-doublet model $m_{H^+} > 0.97$ tanβ GeV (90% CL).
[121] COARASA 97 reanalyzed the constraint on the ($m_{H^\pm}$,tanβ) plane derived from the inclusive $B \to \tau\nu_\tau X$ branching ratio in GROSSMAN 95B and BUSKULIC 95. They show that the constraint is quite sensitive to supersymmetric one-loop effects.
[122] GUCHAIT 97 studies the constraints on m_{H^+} set by Tevatron data on $\ell\tau$ final states in $t\overline{t} \to (Wb)(Hb)$, $W \to \ell\nu$, $H \to \tau\nu_\tau$. See Fig. 2 for the excluded region.
[123] MANGANO 97 reconsiders the limit in ACCIARRI 97F including the effect of the potentially large $B_c \to \tau\nu_\tau$ background to $B_u \to \tau\nu_\tau$ decays. Stronger limits are obtained.
[124] STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^+} > 1.5$ tanβ GeV (90% CL) for a two-doublet model. See also STAHL 94.
[125] ABE 96G search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. For the currently observed value of the top mass, the search is not sensitive enough to exclude a charged Higgs boson of any mass.
[126] ALEXANDER 96I search for the final states $H^+H^- \to \tau\nu_\tau\tau\nu_\tau$, $\tau\nu_\tau c\overline{s}$, $c\overline{s}\overline{c}s$. Limit for $B(\tau\nu_\tau) = 1$ is 45.5 GeV.
[127] ALAM 95 measure the inclusive $b \to s\gamma$ branching ratio at $\Upsilon(4S)$ and give $B(b \to s\gamma) < 4.2 \times 10^{-4}$ (95% CL), which translates to the limit $m_{H^+} >[244 + 63/(\tan\beta)^{1.3}]$ GeV in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.
[128] BUSKULIC 95 give a limit $m_{H^+} > 1.9$ tanβ GeV (90%CL) for Type-II models from $b \to \tau\nu_\tau X$ branching ratio, as proposed in GROSSMAN 94.
[129] ABREU 94O study $H^+H^- \to c\overline{s}s\overline{c}$ (four-jet final states) and $H^+H^- \to \tau\nu_\tau\tau\nu_\tau$. Limit for $B(\tau\nu_\tau)$= 1 is 45.4 GeV.
[130] HEWETT 93 and BARGER 93 analyze charged Higgs contribution to $b \to s\gamma$ in two-doublet models with the CLEO limit $B(b \to s\gamma) < 8.4 \times 10^{-4}$ (90% CL) and find lower limits on $m_{H^\pm}$ in the type of model (model II) in which different Higgs are responsible for up-type and down-type quark masses. HEWETT 93 give m_{H^+} >110 (70) GeV for m_t >150 (120) GeV using m_b = 5 GeV. BARGER 93 give m_{H^+} >155 GeV for m_t = 150 GeV using m_b = 4.25 GeV. The authors employ leading logarithmic QCD corrections and emphasize that the limits are quite sensitve to m_b.
[131] BELANGER 93 make an analysis similar to BARGER 93 and HEWETT 93 with an improved CLEO limit $B(b \to s\gamma) < 5.4 \times 10^{-4}$ (95%CL). For the Type II model, the limit m_{H^+} >540 (300) GeV for m_t >150 (120) GeV is obtained. The authors employ leading logarithmic QCD corrections.
[132] ADRIANI 92G limit improves to 44 GeV if $B(\tau\nu_\tau) > 0.4$.
[133] Studied $H^+H^- \to (\tau\nu) + (\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons, $H^+H^- \to$ hadrons.
[134] DECAMP 92 limit improves to 45.3 GeV for $B(\tau\nu)$=1.
[135] YUZUKI 91 assume photon exchange. The limit is valid for any decay mode $H^+ \to e\nu$, $\mu\nu$, $\tau\nu$, $q\overline{q}$ with five flavors. For $B(\ell\nu) = 1$, the limit improves to 25.0 GeV.
[136] ABREU 90B limit improves to 36 GeV for $B(\tau\nu) = 1$.
[137] ADACHI 90B limit improves to 22 GeV for $B(\tau\nu) = 0.6$.
[138] ADEVA 90M limit improves to 42.5 GeV for $B(\tau\nu) = 1$.
[139] AKRAWY 90K limit improves to 43 GeV for $B(\tau\nu) = 1$.
[140] If $B(H^+ \to \tau^+\nu)$ = 100%, the DECAMP 90I limit improves to 43 GeV.
[141] SMITH 90B limit applies for v_2/v_1 > 2 in a model in which H_2 couples to u-type quarks and charged leptons.
[142] Studied $H^+H^- \to (\tau\nu) + (\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons. Search for muon opposite hadronic shower.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>45.6	95	[143] ACTON 92M	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[144] GORDEEV 97	SPEC	muonium conversion
		[145] ASAKA 95	THEO	
>30.4	95	[146] ACTON 92M	OPAL	$T_3(H^{++})$= +1
>25.5	95	[146] ACTON 92M	OPAL	$T_3(H^{++})$= 0
none 6.5–36.6	95	[147] SWARTZ 90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[147] SWARTZ 90	MRK2	$T_3(H^{++}) = 0$

[143] ACTON 92M limit assumes $H^{\pm\pm} \to \ell^\pm\ell^\pm$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.
[144] GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa copulings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muonium-antimuonium conversion, see the muon Particle Listings.
[145] ASAKA 95 point out that H^{++} decays dominantly to four fermions in a large region of parameter space where the limit of ACTON 92M from the search of dilepton modes does not apply.
[146] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.
[147] SWARTZ 90 assume $H^{\pm\pm} \to \ell^\pm\ell^\pm$ (any flavor). The limits are valid for the Higgs-lepton coupling $g(H\ell\ell) \gtrsim 7.4 \times 10^{-7}/[m_H/{\rm GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

H^0 and $H^\pm$ REFERENCES

ABREU 98E EPJ C2 1 P. Abreu+ (DELPHI Collab.)
ABREU 98F PL B420 140 P. Abreu+ (DELPHI Collab.)
ACCIARRI 98B PL B418 389 M. Acciarri+ (L3 Collab.)
ACKERSTAFF 98B EPJ C1 31 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 98H EPJ C1 425 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 98I PL B426 180 K. Ackerstaff+ (OPAL Collab.)
CHANOWITZ 98 PRL 80 2521 M. Chanowitz
ABBANEO 97 CERN-PPE/97-154 D. Abbaneo+
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and the LEP Electroweak Working Group.
ABE 97L PRL 79 357 F. Abe+ (CDF Collab.)
ABE 97W PRL 79 3819 F. Abe+ (CDF Collab.)
ACCIARRI 97F PL B396 327 M. Acciarri+ (L3 Collab.)
ACCIARRI 97N PL B411 330 M. Acciarri+ (L3 Collab.)
ACCIARRI 97O PL B411 373 M. Acciarri+ (L3 Collab.)
ACKERSTAFF 97E PL B393 231 K. Ackerstaff+ (OPAL Collab.)
ALEXANDER 97 ZPHY C73 189 G. Alexander+ (OPAL Collab.)
AMMAR 97B PRL 78 4686 R. Ammar+ (CLEO Collab.)
BARATE 97O PL B412 155 R. Barate+ (ALEPH Collab.)
BARATE 97P PL B412 173 R. Barate+ (ALEPH Collab.)
BOCK 97 CERN-EP/98-046 P. Bock+
ALEPH, DELPHI, L3, and OPAL Collaborations, and the LEP Higgs Boson Searches Working Group
COARASA 97 PL B406 337 J.A. Coarasa, R.A. Jimenez, J. Sola
DEBOER 97B ZPHY C75 627 W. de Boer, A. Dabelstein, W. Hollik+
DEGRASSI 97 PL B394 188 G. Degrassi, P. Gambino, A. Sirlin (MPIM, NYU)
DITTMAIER 97 PL B391 420 S. Dittmaier, D. Schildknecht (BIEL)
GORDEEV 97 PAN 60 1164 V.A. Gordeev+ (PNPI)
Translated from YAF 60 1291.

GUCHAIT	97	PR D55 7263	M. Guchait, D.P. Roy	(TATA)
KEITH	97	PR D56 R5306	E. Keith, E. Ma, D.P. Roy	
KRAWCZYK	97	PR D55 6968	M. Krawczyk, J. Zochowski	(WARS)
MANGANO	97	PL B410 299	M. Mangano, S. Slabospitsky	
RENTON	97	IJMP A12 4109	P.B. Renton	
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ABE	96G	PR D54 735	+	(CDF Collab.)
ACCIARRI	96I	PL B385 454	+	(L3 Collab.)
ACCIARRI	96J	PL B388 409	+	(L3 Collab.)
ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz+	
			The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and the LEP Electroweak Working Group	
ALEXANDER	96H	ZPHY C71 1	+	(OPAL Collab.)
ALEXANDER	96I	PL B370 174	+	(OPAL Collab.)
ALEXANDER	96L	PL B377 273	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96K	PL B373 246	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96R	PL B384 427	+	(ALEPH Collab.)
DITTMAIER	96	PL B386 247	+Schildknecht, Weiglein	(BIEL, KARL)
ELLIS	96C	PL B389 321	+Fogli, Lisi	(CERN, BARI)
GURTU	96	PL B385 415		(TATA)
PDG	96	PR D54 1		
ABREU	95H	ZPHY C67 69	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
ALAM	95	PRL 74 2885	+Kim, Ling, Mahmood+	(CLEO Collab.)
ASAKA	95	PL B345 36	+Hikasa	(TOHOK)
BUSKULIC	95	PL B343 444	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
CHANKOWSKI	95	PL B356 307	+Pokorski	(WARS, MPIM)
ERLER	95	PR D52 441	+Langacker	(PENN)
GROSSMAN	95B	PL B357 630	Y. Grossman, H. Haber, Y. Nir	
MATSUMOTO	95	MPL A10 2553		(KEK)
ROSIEK	95	PL B341 419	+Sopczak	(IFIC, CERN)
ABREU	94G	NP B421 3	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	94O	ZPHY C64 183	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
AKERS	94B	PL B327 397	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94I	ZPHY C64 1	+Alexander, Allison, Anderson, Arcelli, Asai+	(OPAL Collab.)
ELLIS	94B	PL B333 118	+Fogli, Lisi	(CERN, BARI)
GROSSMAN	94	PL B332 373	Y. Grossman, Z. Ligeti	
GURTU	94	MPL A9 3301		(TATA)
MONTAGNA	94	PL B335 484	+Nicrosini, Passarino, Piccinini	(INFN, PAVI, CERN, TORI)
STAHL	94	PL B324 121	A. Stahl	(BONN)
ADRIANI	93C	PL B303 391	+Aguilar-Benitez, Ahlen, Alcaraz, Aloiso+	(L3 Collab.)
BARGER	93	PRL 70 1368	+Berger, Phillips	(WISC, RAL)
BELANGER	93	PR D48 5419	+Geng, Turcotte	(MONT, ISU, AMES)
BRAHMACH...	93	PR D48 4224	Brahmachari, Joshipura, Rindani+	(AHMED, TATA, CERN)
BUSKULIC	93H	PL B313 299	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	93I	PL B313 312	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
ELLIS	93	NP B393 3	+Fogli, Lisi	(CERN, BARI)
GROSS	93	IJMP A8 407	+Yepes	(CERN)
HEWETT	93	PRL 70 1045		(ANL, OREG)
LOPEZ-FERN...	93	PL B312 240	Lopez-Fernandez, Romao+	(CERN, LISB, VALE)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ABREU	92J	NP B373 3	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ACTON	92M	PL B295 347	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADEVA	92B	PL B283 454	+Adriani, Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92G	PL B294 457	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
Also	93B	ZPHY C57 355	Adriani, Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
BUSKULIC	92	PL B285 309	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
PICH	92	NP B388 31	+Prades, Yepes	(CERN, CPPM)
ABREU	91B	ZPHY C51 25	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ACTON	91	PL B268 122	+Alexander, Allison, Allport+	(OPAL Collab.)
ADEVA	91	PL B257 450	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	91D	PL B262 155	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	91	PL B253 511	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	91C	ZPHY C49 1	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
BLUEMLEIN	91	ZPHY C51 341	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
DECAMP	91F	PL B262 139	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	91I	PL B265 475	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
YUZUKI	91	PL B267 309	+Haba, Abe, Amako, Arai, Asano+	(VENUS Collab.)
ABE	90E	PR D41 1717	+Amidei, Appollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	90B	PL B241 449	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90C	NP B342 1	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90E	PL B245 276	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90I	HEP-90 Singapore unpub CERN-PPE/90-163	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ADACHI	90B	PL B240 513	+Aihara, Doeser, Enomoto+	(TOPAZ Collab.)
ADEVA	90H	PL B248 203	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90M	PL B252 511	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90N	PL B252 518	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90R	PL B251 311	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90C	PL B236 224	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90K	PL B242 299	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90P	PL B251 211	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90	PL B236 233	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90E	PL B237 291	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90H	PL B241 141	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90I	PL B241 623	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	90M	PL B245 289	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	90N	PL B246 306	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
KOMAMIYA	90	PRL 64 2881	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
SMITH	90B	PR D42 949	+McNeil, Breedon, Kim, Ko+	(AMY Collab.)
SWARTZ	90	PRL 64 2877	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
CAHN	89	RPP 52 389		
DAVIER	89	PL B229 150	+Nguyen Ngoc	(LALO)
KOMAMIYA	89	PR D40 721	+Fordham, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
LOW	89	PL B228 548	+Xu, Abashian, Gotow, Hu, Mattson+	(AMY Collab.)
SHER	89	PRPL 179 273		
SNYDER	89	PL B229 169	+Murray, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
BEHREND	87	PL B193 376	+Buerger, Criegee, Dainton+	(CELLO Collab.)
FRANZINI	87	PR D35 2883	+Son, Tuts, Youssef, Zhao+	(CUSB Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
EICHTEN	86	PR D34 1547	+Hinchliffe, Lane, Quigg+	(FNAL, LBL, OSU)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
AKERLOF	85	PL 156B 271	+Bonvicini, Chapman, Errede+	(HRS Collab.)
ALBRECHT	85J	ZPHY C29 167	+Binder, Harder+	(ARGUS Collab.)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
ASH	85C	PRL 54 2477	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85L	PL 155B 288	+Becker, Cords, Felst, Hagiwara+	(JADE Collab.)
BEHREND	85	PL 161B 182	+Burger, Criegee, Fenner+	(CELLO Collab.)
FELDMAN	85	PRL 54 2289	+Abrams, Amidei, Baden+	(Mark II Collab.)

Heavy Bosons Other Than Higgs Bosons, Searches for

We list here various limits on charged and neutral heavy vector bosons (other than W's and Z's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons.

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS for W' below are also valid for W_R if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W_R mixing angle ζ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 549		[1] BARENBOIM	97	RVUE	μ decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 220	95	[2] STAHL	97	RVUE	τ decay
> 220	90	[3] ALLET	96	CNTR	β^+ decay
> 281	90	[4] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[5] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[6] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[7] SEVERIJNS	93	CNTR	β^+ decay
		[8] IMAZATO	92	CNTR	K^+, decay
> 475	90	[9] POLAK	92B	RVUE	μ decay
> 240	90	[10] AQUINO	91	RVUE	Neutron decay
> 496	90	[10] AQUINO	91	RVUE	Neutron and muon decay
> 700		[11] COLANGELO	91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[12] POLAK	91	RVUE	μ decay
[none 540–23000]		[13] BARBIERI	89B	ASTR	SN 1987A; light ν_R
> 300	90	[14] LANGACKER	89B	RVUE	General
> 160	90	[15] BALKE	88	CNTR	$\mu \rightarrow e\nu\overline{\nu}$
> 406	90	[16] JODIDIO	86	ELEC	Any ζ
> 482	90	[16] JODIDIO	86	ELEC	$\zeta = 0$
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[17] STOKER	85	ELEC	Any ζ
> 475	95	[17] STOKER	85	ELEC	ζ <0.041
		[18] BERGSMA	83	CHRM	$\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	[19] CARR	83	ELEC	μ^+ decay
>1600		[20] BEALL	82	THEO	$m_{K^0_L} - m_{K^0_S}$
[> 4000]		STEIGMAN	79	COSM	Nucleosynthesis; light ν_R

[1] The quoted limit is from μ decay parameters. BARENBOIM 97 also evaluate limit from K_L-K_S mass difference.

[2] STAHL 97 limit is from fit to τ-decay parameters.

[3] ALLET 96 measured polarization-asymmetry correlaton in $^{12}N\beta^+$ decay. The listed limit assumes zero L-R mixing.

[4] KUZNETSOV 95 limit is from measurements of the asymmetry $\langle \vec{p}_\nu \cdot \sigma_n \rangle$ in the β decay of polarized neutrons. Zero mixing assumed. See also KUZNETSOV 94B.

[5] KUZNETSOV 94B limit is from measurements of the asymmetry $\langle \vec{p}_\nu \cdot \sigma_n \rangle$ in the β decay of polarized neutrons. Zero mixing assumed.

[6] BHATTACHARYYA 93 uses Z-Z' mixing limit from LEP '90 data, assuming a specific Higgs sector of $SU(2)_L \times SU(2)_R \times U(1)$ gauge model. The limit is for m_t=200 GeV and slightly improves for smaller m_t.

[7] SEVERIJNS 93 measured polarization-asymmetry correlation in $^{107}In\,\beta^+$ decay. The listed limit assumes zero L-R mixing. Value quoted here is from SEVERIJNS 94 erratum.

[8] IMAZATO 92 measure positron asymmetry in $K^+ \rightarrow \mu^+\nu_\mu$ decay and obtain $\xi P_\mu > 0.990$ (90%CL). If W_R couples to $u\overline{s}$ with full weak strength (V^R_{us}=1), the result corresponds to $m_{W_R} >$653 GeV. See their Fig. 4 for m_{W_R} limits for general $|V^R_{us}|^2 = 1 - |V^R_{ud}|^2$.

[9] POLAK 92B limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Supersedes POLAK 91.

[10] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right symmetry assumed. Stronger of the two limits also includes muon decay results.

[11] COLANGELO 91 limit uses hadronic matrix elements evaluated by QCD sum rule and is less restrictive than BEALL 82 limit which uses vacuum saturation approximation. Manifest left-right symmetry assumed.

[12] POLAK 91 limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Superseded by POLAK 92B.

[13] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[14] LANGACKER 89B limit is for any ν_R mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.

[15] BALKE 88 limit is for $m_{\nu_{eR}} = 0$ and $m_{\nu_{\mu R}} \leq 50$ MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.

[16] JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point e^+ spectrum in the decay of the highly polarized μ^+.

[17] STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay e^+ spectrum asymmetry above 46 MeV/c using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.

[18] BERGSMA 83 set limit $m_{W_2}/m_{W_1} >1.9$ at CL = 90%.

[19] CARR 83 is TRIUMF experiment with a highly polarized μ^+ beam. Looked for deviation from $V-A$ at the high momentum end of the decay e^+ energy spectrum. Limit from previous world-average muon polarization parameter is m_{W_R} >240 GeV. Assumes a light right-handed neutrino.

[20] BEALL 82 limit is obtained assuming that W_R contribution to K_L^0–K_S^0 mass difference is smaller than the standard one, neglecting the top quark contributions. Manifest left-right symmetry assumed.

Limit on W_L-W_R Mixing Angle ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_R assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 0.0333		[21] BARENBOIM	97	RVUE	μ decay
$<$ 0.04	90	[22] MISHRA	92	CCFR	νN scattering
-0.0006 to 0.0028	90	[23] AQUINO	91	RVUE	
[none 0.00001–0.02]		[24] BARBIERI	89B	ASTR	SN 1987A
$<$ 0.040	90	[25] JODIDIO	86	ELEC	μ decay
-0.056 to 0.040	90	[25] JODIDIO	86	ELEC	μ decay

[21] The quoted limit is from μ decay parameters. BARENBOIM 97 also evaluate limit from K_L-K_S mass difference.

[22] MISHRA 92 limit is from the absence of extra large-x, large-y $\overline{\nu}_\mu N \rightarrow \overline{\nu}_\mu X$ events at Tevatron, assuming left-handed ν and right-handed $\overline{\nu}$ in the neutrino beam. The result gives $\zeta^2(1-2m^2_{W_1}/m^2_{W_2}) < 0.0015$. The limit is independent of ν_R mass.

[23] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.

[24] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[25] First JODIDIO 86 result assumes $m_{W_R}=\infty$, second is for unconstrained m_{W_R}.

THE W' SEARCHES

Written October 1997 by K.S. Babu, C. Kolda, and J. March-Russell (IAS/Princeton).

Any electrically charged gauge boson outside of the Standard Model is generically denoted W'. A W' always couples to two different flavors of fermions, similar to the W boson. In particular, if a W' couples quarks to leptons it is a leptoquark gauge boson.

The most attractive candidate for W' is the W_R gauge boson associated with the left-right symmetric models [1]. These models seek to provide a spontaneous origin for parity violation in weak interactions. Here the gauge group is extended to $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ with the Standard Model hypercharge identified as $Y = T_{3R} + (B\text{-}L)/2$, T_{3R} being the third component of $\mathrm{SU}(2)_R$. The fermions transform under the gauge group in a left-right symmetric fashion: $q_L(3,2,1,1/3) + q_R(3,1,2,1/3)$ for quarks and $\ell_L(1,2,1,-1) + \ell_R(1,1,2,-1)$ for leptons. Note that the model requires the introduction of right-handed neutrinos, which can facilitate the see-saw mechanism for explaining the smallness of the ordinary neutrino masses. A Higgs bidoublet $\Phi(1,2,2,0)$ is usually employed to generate quark and lepton masses and to participate in the electroweak symmetry breaking. Under left-right (or parity) symmetry, $q_L \leftrightarrow q_R$, $\ell_L \leftrightarrow \ell_R$, $W_L \leftrightarrow W_R$ and $\Phi \leftrightarrow \Phi^\dagger$.

After spontaneous symmetry breaking, the two W bosons of the model, W_L and W_R, will mix. The physical mass eigenstates are denoted as

$$W_1 = \cos\zeta\, W_L + \sin\zeta\, W_R, \qquad W_2 = -\sin\zeta\, W_L + \cos\zeta\, W_R \quad (1)$$

with W_1 identified as the observed W boson. The most general Lagrangian that describes the interactions of the $W_{1,2}$ with the quarks can be written as [2]

$$\mathcal{L} = -\frac{1}{\sqrt{2}} \overline{u} \gamma_\mu \left[\left(g_L \cos\zeta\, V^L P_L - g_R e^{i\omega} \sin\zeta\, V^R P_R \right) W_1^\mu \right.$$
$$\left. + \left(g_L \sin\zeta\, V^L P_L + g_R e^{i\omega} \cos\zeta\, V^R P_R \right) W_2^\mu \right] d + h.c. \quad (2)$$

where $g_{L,R}$ are the $\mathrm{SU}(2)_{L,R}$ gauge couplings, $P_{L,R} = (1 \mp \gamma_5)/2$ and $V^{L,R}$ are the left- and right-handed CKM matrices in the quark sector. The phase ω reflects a possible complex mixing parameter in the W_L–W_R mass-squared matrix. Note that there is CP violation in the model arising from the right-handed currents even with only two generations. The Lagrangian for leptons is identical to that for quarks, with the replacements $u \rightarrow \nu$, $d \rightarrow e$ and the identification of $V^{L,R}$ with the CKM matrices in the leptonic sector.

If parity invariance is imposed on the Lagrangian, then $g_L = g_R$. Furthermore, the Yukawa coupling matrices that arise from coupling to the Higgs bidoublet Φ will be Hermitian. If in addition the vacuum expectation values of Φ are assumed to be real, the quark and lepton mass matrices will also be Hermitian, leading to the relation $V^L = V^R$. Such models are called *manifest* left-right symmetric models and are approximately realized with a minimal Higgs sector [3]. If instead parity and CP are both imposed on the Lagrangian, then the Yukawa coupling matrices will be real symmetric and, after spontaneous CP violation, the mass matrices will be complex symmetric. In this case, which is known in the literature as *pseudo-manifest* left-right symmetry, $V^L = (V^R)^*$.

Indirect constraints: In minimal version of manifest or pseudo-manifest left-right symmetric models with $\omega = 0$ or π, there are only two free parameters, ζ and M_{W_2}, and they can be constrained from low energy processes. In the large M_{W_2} limit, stringent bounds on the angle ζ arise from three processes. (i) Nonleptonic K decays: The decays $K \rightarrow 3\pi$ and $K \rightarrow 2\pi$ are sensitive to small admixtures of right-handed currents. Assuming the validity of PCAC relations in the Standard Model it has been argued in Ref. 4 that the success in the $K \rightarrow 3\pi$ prediction will be spoiled unless $|\zeta| \leq 4 \times 10^{-3}$. (ii) $b \rightarrow s\gamma$: The amplitude for this process has an enhancement factor m_t/m_b relative to the Standard Model and thus can be used to constrain ζ yielding the limit $-0.01 \leq \zeta \leq 0.003$ [5]. (iii) Universality in weak decays: If the right-handed neutrinos are heavy, the right-handed admixture in the charged current will contribute to β decay and K decay, but not to the μ decay. This will modify the extracted values of V^L_{ud} and V^L_{us}. Demanding that the difference not upset the three generation unitarity of the CKM matrix, a bound $|\zeta| \leq 10^{-3}$ has been derived [6].

If the ν_R are heavy, leptonic and semileptonic processes do not constrain ζ since the emission of ν_R will not be kinematically allowed. However, if the ν_R is light enough to be emitted in μ decay and β decay, stringent limits on ζ do arise. For example, $|\zeta| \leq 0.039$ can be obtained from polarized μ decay [7] in the large M_{W_2} limit of the manifest left-right model. Alternatively, in the $\zeta = 0$ limit, there is a constraint $M_{W_2} \geq 484$ GeV from direct W_2 exchange. For the constraint on the case in which M_{W_2} is not taken to be heavy, see Ref. 2. There are also cosmological and astrophysical constraints on M_{W_2} and ζ in scenarios with a light ν_R. During nucleosynthesis the process $e^+e^- \to \nu_R\overline{\nu}_R$, proceeding via W_2 exchange, will keep the ν_R in equilibrium leading to an overproduction of ^{4}He unless M_{W_2} is greater than about 1 TeV [8]. Likewise the ν_{eR} produced via $e_R^- p \to n\nu_R$ inside a supernova must not drain too much of its energy, leading to limits $M_{W_2} > 16$ TeV and $|\zeta| \leq 3 \times 10^{-5}$ [9]. Note that models with light ν_R do not have a see-saw mechanism for explaining the smallness of the neutrino masses, though other mechanisms may arise in variant models [10].

The mass of W_2 is severely constrained (independent of the value of ζ) from K_L–K_S mass-splitting. The box diagram with exchange of one W_L and one W_R has an anomalous enhancement and yields the bound $M_{W_2} \geq 1.6$ TeV [11] for the case of manifest or pseudo-manifest left-right symmetry. If the ν_R have Majorana masses, another constraint arises from neutrinoless double β decay. Combining the experimental limit from ^{76}Ge decay with arguments of vacuum stability, a limit of $M_{W_2} \geq 1.1$ TeV has been obtained [12].

Direct search limits: Limits on M_{W_2} from direct searches depend on the available decay channels of W_2. If ν_R is heavier than W_2, the decay $W_2^+ \to \ell_R^+\nu_R$ will be forbidden kinematically. Assuming that ζ is small, the dominant decay of W_2 will be into dijets. UA2 [13] has excluded a W_2 in the mass range of 100 to 251 GeV in this channel. DØ excludes the mass range of 340 to 680 GeV [14], while CDF excludes the mass range of 300 to 420 GeV for such a W_2 [15]. If ν_R is lighter than W_2, the decay $W_2^+ \to e_R^+\nu_R$ is allowed. The ν_R can then decay into $e_R W_R^*$, leading to an $eejj$ signature. DØ has a limit of $M_{W_2} > 720$ GeV if $m_{\nu_R} \ll M_{W_2}$; the bound weakens, for example, to 650 GeV for $m_{\nu_R} = M_{W_2}/2$ [16]. CDF finds $M_{W_2} > 652$ GeV if ν_R is stable and much lighter than W_2 [17]. All of these limits assume manifest or pseudo-manifest left-right symmetry. See [16] for some variations in the limits if the assumption of left-right symmetry is relaxed.

Alternative models: W' gauge bosons can also arise in other models. We shall briefly mention some such popular models, but for details we refer the reader to the original literature. The *alternate* left-right model [18] is based on the same gauge group as the left-right model, but arises in the following way: In E_6 unification, there is an option to identify the right-handed down quarks as $SU(2)_R$ singlets or doublets. If they are $SU(2)_R$ doublets, one recovers the conventional left-right model; if they are singlets it leads to the alternate left-right model. A similar ambiguity exists in the assignment of left-handed leptons; the alternate left-right model assigns them to a $(1,2,2,0)$ multiplet. As a consequence, the ordinary neutrino remains exactly massless in the model. One important difference from the usual left-right model is that the limit from the K_L–K_S mass difference is no longer applicable, since the d_R do not couple to the W_R. There is also no limit from polarized μ decay, since the $SU(2)_R$ partner of e_R can receive a large Majorana mass. Other W' models include the un-unified Standard Model of Ref. 19 where there are two different SU(2) gauge groups, one each for the quarks and leptons; models with separate SU(2) gauge factors for each generation [20]; and the $SU(3)_C \times SU(3)_L \times U(1)$ model of Ref. 21.

Leptoquark gauge bosons: The $SU(3)_C \times U(1)_{B-L}$ part of the gauge symmetry discussed above can be embedded into a simple $SU(4)_C$ gauge group [22]. The model then will contain leptoquark gauge boson as well, with couplings of the type $\{(\overline{e}_L\gamma_\mu d_L + \overline{\nu}_L\gamma_\mu u_L)W'^\mu + (L \to R)\}$. The best limit on such leptoquark W' comes from nonobservation of $K_L \to \mu e$, which requires $M_{W'} \geq 1400$ TeV; for the corresponding limits on less conventional leptoquark flavor structures, see Ref. 23. Thus such a W' is inaccessible to direct searches with present machines which are sensitive to vector leptoquark masses of order 300 GeV only.

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MASS LIMITS for W' (A Heavy-Charged Vector Boson Other Than W) in Hadron Collider Experiments

Couplings of W' to quarks and leptons are taken to be identical with those of W. The following limits are obtained from $p\overline{p} \to W'X$ with W' decaying to the mode indicated in the comments. New decay channels (*e.g.*, $W' \to WZ$) are assumed to be suppressed. UA1 and UA2 experiments assume that the $t\overline{b}$ channel is not open.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>720	95	[26] ABACHI 96C	D0	$W' \to e\nu_e$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 300–420	95	[27] ABE 97G	CDF	$W' \to q\overline{q}$
>610	95	[28] ABACHI 95E	D0	$W' \to e\nu_e$ and $W' \to \tau\nu_\tau \to e\nu\nu\overline{\nu}$
>652	95	[29] ABE 95M	CDF	$W' \to e\nu_e$
>251	90	[30] ALITTI 93	UA2	$W' \to q\overline{q}$
none 260–600	95	[31] RIZZO 93	RVUE	$W' \to q\overline{q}$
>520	95	[32] ABE 91F	CDF	$W' \to e\nu, \mu\nu$
none 101–158	90	[33] ALITTI 91	UA2	$W' \to q\overline{q}$
>220	90	[34] ALBAJAR 89	UA1	$W' \to e\nu$
>209	90	[35] ANSARI 87D	UA2	$W' \to e\nu$
>210	90	[36] ARNISON 86B	UA1	$W' \to e\nu$
>170	90	[37] ARNISON 83D	UA1	$W' \to e\nu$

[26] For bounds on W_R with nonzero right-handed mass, see Fig. 5 from ABACHI 96C.

[27] ABE 97G search for new particle decaying to dijets.

[28] ABACHI 95E assume that the decay $W' \to WZ$ is suppressed and that the neutrino from W' decay is stable and has a mass significantly less $m_{W'}$.

[29] ABE 95M assume that the decay $W' \to WZ$ is suppressed and the (right-handed) neutrino is light, noninteracting, and stable. If m_ν=60 GeV, for example, the effect on the mass limit is neglibible.

[30] ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes $\Gamma(W')/m_{W'} = \Gamma(W)/m_W$ and $B(W' \to JJ) = 2/3$. This corresponds to W_R with $m_{\nu_R} > m_{W_R}$ (no leptonic decay) and $W_R \to t\overline{b}$ allowed. See their Fig. 4 for limits in the $m_{W'}$–$B(q\overline{q})$ plane.

[31] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[32] ABE 91F assume leptonic branching ratio of 1/12 for each lepton flavor. The limit from the $e\nu$ ($\mu\nu$) mode alone is 490 (435) GeV. These limits apply to W_R if $m_{\nu_R} \lesssim 15$ GeV and ν_R does not decay in the detector. Cross section limit $\sigma \cdot B < (1\text{–}10)$ pb is given for $m_{W'} = 100$–550 GeV; see Fig. 2.

[33] ALITTI 91 search is based on two-jet invariant mass spectrum, assuming $B(W' \to q\overline{q}) = 67.6\%$. Limit on $\sigma \cdot B$ as a function of two-jet mass is given in Fig. 7.

[34] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')\, B(e\nu) < 4.1$ pb (90% CL).

[35] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{W'}$–$[(g_{W'q})^2\, B(W' \to e\overline{\nu})]$ plane. Note that the quantity $(g_{W'q})^2\, B(W' \to e\overline{\nu})$ is normalized to unity for the standard W couplings.

[36] ARNISON 86B find no excess at large p_T in 148 $W \to e\nu$ events. Set limit $\sigma \times B(e\nu) < 10$ pb at CL = 90% at E_{cm} = 546 and 630 GeV.

[37] ARNISON 83D find among 47 $W \to e\nu$ candidates no event with excess p_T. Also set $\sigma \times B(e\nu) < 30$ pb with CL = 90% at E_{cm} = 540 GeV.

THE Z' SEARCHES

Written October 1997 by K.S. Babu, C. Kolda, and J. March-Russell (IAS/Princeton).

If the Standard Model is enhanced by additional gauge symmetries or embedded into a larger gauge group, there will arise new heavy gauge bosons, some of which generically are electrically neutral. Such a gauge boson is called a Z'. Consider the most general renormalizable Lagrangian describing the complete set of interactions of the neutral gauge bosons among themselves and with fermions, which is that of the Standard Model plus the following new pieces [1,2,3]:

$$\begin{aligned}\mathcal{L}_{Z'} = &-\frac{1}{4}\widehat{F}'_{\mu\nu}\widehat{F}'^{\mu\nu} - \frac{\sin\chi}{2}\widehat{F}'_{\mu\nu}\widehat{F}^{\mu\nu} + \frac{1}{2}\widehat{M}^2_{Z'}\widehat{Z}'_\mu\widehat{Z}'^\mu \\ &+ \delta\widehat{M}^2\,\widehat{Z}'_\mu\widehat{Z}^\mu - \frac{\widehat{g}'}{2}\sum_i \overline{\psi}_i\gamma^\mu(f^i_V - f^i_A\gamma^5)\psi_i\widehat{Z}'_\mu \end{aligned} \quad (1)$$

where $\widehat{F}_{\mu\nu}, \widehat{F}'_{\mu\nu}$ are the field strength tensors for the hypercharge $\widehat{B}_\mu$ gauge boson and the Z' respectively before any diagonalizations are performed, ψ_i are the matter fields with Z' vector and axial charges f^i_V and f^i_A, and $\widehat{Z}_\mu$ is the electroweak Z boson in this basis. (See the Review on "Electroweak Model and Constraints on New Physics" for the Standard Model pieces of the Lagrangian.) The mass terms are assumed to come from spontaneous symmetry breaking via scalar expectation values. The above Lagrangian is general to all abelian and non-abelian extensions, except that $\chi = 0$ for the non-abelian case since then $\widehat{F}'_{\mu\nu}$ is not gauge invariant. Most analyses take $\chi = 0$ even for the abelian case.

Going to the physical eigenbasis requires diagonalizing both the gauge kinetic and mass terms, with mass eigenstates denoted Z_1 and Z_2, where we choose Z_1 to be the observed Z boson. The interaction Lagrangian for Z_1 has the form, to leading order in the mixing angle ξ ($s_W \equiv \sin\theta_W$, etc.):

$$\begin{aligned}\mathcal{L}_{Z_1} = &-\frac{e}{2s_Wc_W}\left(1+\frac{\alpha T}{2}\right)\overline{\psi}_i\gamma^\mu\left\{\left(g^i_V + \xi\tilde{f}^i_V\right)\right. \\ &\left. - \left(g^i_A + \xi\tilde{f}^i_A\right)\gamma^5\right\}\psi_i Z_{1\mu}\end{aligned} \quad (2)$$

where

$$\xi \simeq \frac{-\cos\chi(\delta\widehat{M}^2 + \widehat{M}^2_Z s_W\sin\chi)}{\widehat{M}^2_{Z'} - \widehat{M}^2_Z\cos^2\chi + \widehat{M}^2_Z s^2_W\sin^2\chi + 2\,\delta\widehat{M}^2\,s_W\sin\chi}\ . \quad (3)$$

We have made the identifications $g^i_A = T^i_3$, $g^i_V = T^i_3 - 2Q^i s^2_*$, $\tilde{f}^i_{V,A} = (\widehat{g}' s_W c_W / e\cos\chi) f^i_{V,A}$, and s^2_W is identified to be the $s^2_{M_Z}$ defined in the "Electroweak Model and Constraints on New Physics" review. Note that the value of the weak angle that appears in the vector coupling is shifted by the S and T oblique parameters:

$$s^2_* = s^2_W + \frac{1}{s^2_W - c^2_W}\left(\frac{1}{4}\alpha S - c^2_W s^2_W \alpha T\right)\ . \quad (4)$$

Recall that $\rho = 1 + \alpha T$ defines the usual ρ parameter. In the presence of Z–Z' mixing, the oblique parameters receive contributions [4]:

$$\begin{aligned}\alpha S &= 4\xi c^2_W s_W \tan\chi \\ \alpha T &= \xi^2\left(\frac{M^2_{Z_2}}{M^2_{Z_1}} - 1\right) + 2\xi s_W\tan\chi \\ \alpha U &= 0\end{aligned} \quad (5)$$

to leading order in small ξ. These contributions are in addition to those coming from top quark and Higgs boson loops in the Standard Model. (This is in contrast to the "Electroweak

Model and Constraints on New Physics" Review in which oblique parameters are defined to be zero for reference values of m_t and M_H.) Note that nonzero Z–Z' contributions to S arise only in the presence of kinetic mixing.

The corresponding $Z_2\overline{\psi}\psi$ interaction Lagrangian is:

$$\mathcal{L}_{Z_2} = -\frac{e}{2s_W c_W}\overline{\psi}_i\gamma^\mu\left\{\left(h^i_V - g^i_V\xi\right) - \left(h^i_A - g^i_A\xi\right)\gamma^5\right\}\psi_i Z_{2\mu} \tag{6}$$

with the following definitions:

$$\begin{aligned} h^i_V &= \tilde{f}^i_V + \widetilde{s}(T^i_3 - 2Q^i)\tan\chi \\ h^i_A &= \tilde{f}^i_A + \widetilde{s}T^i_3\tan\chi \\ \widetilde{s} &= s_W + \frac{s^3_W}{c^2_W - s^2_W}\left(\frac{1}{4c^2_W}\alpha S - \frac{1}{2}\alpha T\right) \end{aligned} \tag{7}$$

where the last equation defines a weak angle appropriate for the Z_2 interactions.

If the Z' charges are generation-dependent, there exist severe constraints in the first two generations coming from precision measurements such as the K_L–K_S mass splitting and $B(\mu \to 3e)$ owing to the lack of GIM suppression in the Z' interactions; however, constraints on a Z' which couples differently only to the third generation are somewhat weaker. (It will be assumed in the Z-pole constraint section that the Z' couples identically to all three generations of matter; all other results are general.) If the new Z' interactions commute with the Standard Model gauge group, then per generation, there are only five independent $Z'\overline{\psi}\psi$ couplings; we can choose them to be $\tilde{f}^u_V$, $\tilde{f}^u_A$, $\tilde{f}^d_V$, $\tilde{f}^e_V$, and $\tilde{f}^e_A$. All other couplings can be determined in terms of these, *e.g.*, $\tilde{f}^\nu_V = (\tilde{f}^e_V + \tilde{f}^e_A)/2$.

Canonical models: One of the prime motivations for an additional Z' has come from string theory in which certain compactifications lead naturally to an E_6 gauge group, or one of its subgroups. E_6 contains two U(1) factors beyond the Standard Model, a basis for which is formed by the two groups $\mathrm{U}(1)_\chi$ and $\mathrm{U}(1)_\psi$, defined via the decompositions $E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ and $\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi$; one special case often encountered is $\mathrm{U}(1)_\eta$ where $Z_\eta = \sqrt{\frac{3}{8}}Z_\chi + \sqrt{\frac{5}{8}}Z_\psi$. The charges of the SM fermions under these U(1)'s, and a discussion of their experimental signals, can be found in Ref. 5.

It is also common to express experimental bounds in terms of a toy Z' usually denoted Z_{SM}. This Z_{SM}, of arbitrary mass, couples to the SM fermions identically to the usual Z.

Almost all analyses of Z' physics have worked with one of these canonical models and have assumed zero kinetic mixing at the weak scale.

Experimental constraints: There are three primary sets of constraints on the existence of a Z' which will be considered here: precision measurements of neutral-current processes at low energies, Z-pole constraints on Z–Z' mixing, and direct search constraints from production at very high energies. In principle, one usually expects other new states to appear at the same scale as the Z', including its symmetry-breaking sector and any additional fermions necessary for anomaly cancellation. However, because these states are highly model-dependent, we will not include searches for them, or Z' decays to them, in the bounds that follow.

Low-energy constraints: After the breaking of the new gauge group and the usual electroweak breaking, the Z of the Standard Model can mix with the Z', with mixing angle ξ defined above. As already discussed, this Z–Z' mixing implies a shift in the usual oblique parameters [S, T, U defined in Eq. (5)]. Current bounds on S and T translate into stringent constraints on the mixing angle, ξ, requiring $\xi \ll 1$; similar constraints on ξ arise from the LEP Z-pole data. Thus we will only consider the small-ξ limit henceforth.

Whether or not the new gauge interactions are parity violating, stringent constraints can arise from atomic parity violation (APV) and polarized electron-nucleon scattering experiments [6]. At low energies, the effective neutral-current Lagrangian is conventionally written:

$$\mathcal{L}_{\mathrm{NC}} = \frac{G_F}{\sqrt{2}}\sum_{q=u,d}\left\{C_{1q}(\overline{e}\gamma_\mu\gamma^5 e)(\overline{q}\gamma^\mu q) + C_{2q}(\overline{e}\gamma_\mu e)(\overline{q}\gamma^\mu\gamma^5 q)\right\} \ . \tag{8}$$

APV experiments are sensitive only to C_{1u} and C_{1d} (see the "Electroweak Model and Constraints on New Physics" Review for the nuclear weak charge, Q_W, in terms of the C_{1q}) where in the presence of the Z and Z':

$$C_{1q} = 2(1+\alpha T)(g^e_A + \xi\tilde{f}^e_A)(g^q_V + \xi\tilde{f}^q_V) + 2r(h^e_A - \xi g^e_A)(h^q_V - \xi g^q_V) \tag{9}$$

where $r = (M_{Z_1}/M_{Z_2})^2$. The r-dependent terms arise from Z_2 exchange and can interfere constructively or destructively with the Z_1 contribution. In the limit $\xi = r = 0$, this reduces to the Standard Model expression. Polarized electron scattering is sensitive to both the C_{1q} and C_{2q} couplings, again as discussed in the "Electroweak Model and Constraints on New Physics" Review. The C_{2q} can be derived from the expression for C_{1q} with the complete interchange $V \leftrightarrow A$.

Stringent limits also arise from neutrino-hadron scattering. One usually expresses experimental results in terms of the effective 4-fermion operators $(\overline{\nu}\gamma_\mu\nu)(\overline{q}_{L,R}\gamma^\mu q_{L,R})$ with coefficients $(2\sqrt{2}G_F)\epsilon_{L,R}(q)$. (Again, see the "Electroweak Model and Constraints on New Physics" Review.) In the presence of the Z and Z', the $\epsilon_{L,R}(q)$ are given by:

$$\begin{aligned} \epsilon_{L,R}(q) =& \frac{1+\alpha T}{2}\left\{(g^q_V \pm g^q_A)[1 + \xi(\tilde{f}^\nu_V \pm \tilde{f}^\nu_A)] + \xi(\tilde{f}^q_V \pm \tilde{f}^q_A)\right\} \\ &+ \frac{r}{2}\left\{(h^q_V \pm h^q_A)(h^\nu_V \pm h^\nu_A) - \xi(g^q_V \pm g^q_A)(h^\nu_V \pm h^\nu_A)\right. \\ &\left. - \xi(h^q_V \pm h^q_A)\right\} \ . \end{aligned} \tag{10}$$

Again, the r-dependent terms arise from Z_2-exchange.

Z-pole constraints: Electroweak measurements made at LEP and SLC while sitting on the Z resonance are generally sensitive to Z' physics only through the mixing with the Z unless the Z and Z' are very nearly degenerate, a possibility we ignore.

Constraints on the allowed mixing angle and Z couplings arise by fitting all data simultaneously to the *ansatz* of Z–Z' mixing. For any observable, $\mathcal{O}$, the shift in that observable, $\Delta\mathcal{O}$, can be expressed (following the procedure of Ref. 7) as:

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = \mathcal{A}^S_{\mathcal{O}}\,\alpha S + \mathcal{A}^T_{\mathcal{O}}\,\alpha T + \xi \sum_i \mathcal{B}^{(i)}_{\mathcal{O}}\,\tilde{f}^i \qquad (11)$$

where i runs over the 5 independent $Z'\overline{\psi}\psi$ couplings listed earlier (assuming a Z' couplings commute with the generation and gauge symmetries of the Standard Model; this is the only place where we enforce such a restriction). The coefficients $\mathcal{A}^{S,T}_{\mathcal{O}}$ and $\mathcal{B}^{(i)}_{\mathcal{O}}$, which are functions only of the Standard Model parameters, are given in Table 1. The first 5 observables are directly measured at LEP and SLC, while $\overline{A}_e$, $\overline{A}_b$ and $\overline{A}_c$ are measured via the asymmetries $\overline{A}^{(0,f)}_{FB} = \frac{3}{4}\overline{A}_e\overline{A}_f$ and $A^0_{LR} = \overline{A}_e$ as defined in the "Electroweak Model and Constraints on New Physics" Review. As an example, the shift in $\overline{A}_e$ due to Z' physics is given by

$$\frac{\Delta\overline{A}_e}{\overline{A}_e} = -24.9\,\alpha S + 17.7\,\alpha T - 26.7\,\xi\,\tilde{f}^e_V + 2.0\,\xi\,\tilde{f}^e_A\ . \qquad (12)$$

Table 1: Expansion coefficients for shifts in Z-pole observables normalized to the Standard Model value of the observable [7,3].

$\mathcal{O}$	$\mathcal{A}^S_{\mathcal{O}}$	$\mathcal{A}^T_{\mathcal{O}}$	$\mathcal{B}^{Vu}_{\mathcal{O}}$	$\mathcal{B}^{Au}_{\mathcal{O}}$	$\mathcal{B}^{Vd}_{\mathcal{O}}$	$\mathcal{B}^{Ve}_{\mathcal{O}}$	$\mathcal{B}^{Ae}_{\mathcal{O}}$
Γ_Z	−0.49	1.35	−0.89	−0.40	0.37	0.37	0
R_ℓ	−0.39	0.28	−1.3	−0.56	0.52	0.30	4.0
σ_h	0.046	−0.033	0.50	0.22	−0.21	−1.0	−4.0
R_b	0.085	−0.061	−1.4	−2.1	0.29	0	0
R_c	−0.16	0.12	2.7	4.1	−0.59	0	0
$\overline{A}_e$	−24.9	17.7	0	0	0	−26.7	2.0
$\overline{A}_b$	−0.32	0.23	0.71	0.71	−1.73	0	0
$\overline{A}_c$	−2.42	1.72	3.89	−1.49	0	0	0
M^2_W	−0.93	1.43	0	0	0	0	0

High-energy indirect constraints: At $\sqrt{s} < M_{Z_2}$, but off the Z_1 pole, strong constraints on new Z' physics arise from measurements of deviations of asymmetries and leptonic and hadronic cross sections from their Standard Model predictions. These processes are sensitive not only to Z–Z' mixing but also to direct Z_2 exchange primarily through γ–Z_2 and Z_1–Z_2 interference; therefore information on the Z_2 couplings and mass can be extracted that is not accessible via Z–Z' mixing alone.

Far below the Z_2 mass scale, experiment is only sensitive to the scaled Z_2 couplings $(\sqrt{s}/M_{Z_2}) \cdot h^i_{V,A}$ so the Z_2 mass and overall magnitude of the couplings cannot both be extracted. However as $\sqrt{s}$ approaches M_{Z_2} the Z_2 exchange can no longer be approximated by a contact interaction and the mass and couplings can be simultaneously extracted.

Z' studies done before LEP relied heavily on this approach; see, *e.g.*, Ref. 8. LEP has also done similar work using data collected above the Z peak; see, *e.g.*, Ref. 9. For indirect Z' searches at future facilities, see, *e.g.* Refs. 10 and 11.

Direct-search constraints: Finally, high-energy experiments have searched for on-shell Z' (here Z_2) production and decay. Searches can be classified by the initial state off of which the Z' is produced, and the final state into which the Z' decays; we will not include here exotic decays of a Z'. Experiments to date have been sensitive to Z' production via their coupling to quarks ($p\overline{p}$ colliders), to electrons (e^+e^-) or to both (ep).

For a heavy Z' ($M_{Z_2} \gg M_{Z_1}$), the best limits come from $p\overline{p}$ machines via Drell-Yan production and subsequent decay to charged leptons. For $M_{Z_2} > 600\,\mathrm{GeV}$, CDF [12] quotes limits on $\sigma(p\overline{p} \to Z_2X) \cdot B(Z_2 \to \ell^+\ell^-) < 0.04\,\mathrm{pb}$ at 95% C.L. for $\ell = e + \mu$ combined; DØ [13] quotes $\sigma \cdot B < 0.025\,\mathrm{pb}$ for $\ell = e$. For $M_{Z_2} < 600\,\mathrm{GeV}$, the mass dependence is complicated and one should refer to the original literature. For studies of the search capabilities of future facilities, see *e.g.* Ref. 10.

If the Z' has suppressed, or no, couplings to leptons (*i.e.*, it is leptophobic) then experimental sensitivities are much weaker. In particular, searches for a Z' via hadronic decays at DØ [14] are able to rule out a Z' with quark couplings identical to those of the Z only in the mass range $365\,\mathrm{GeV} < M_{Z_2} < 615\,\mathrm{GeV}$; CDF [15] cannot exclude even this range. Additionally, UA2 [16] finds $\sigma \cdot B(Z' \to jj) < 11.7\,\mathrm{pb}$ at 90% C.L. for $M_{Z'} > 200\,\mathrm{GeV}$ and more complicated bounds in the range $130\,\mathrm{GeV} < M_{Z'} < 200\,\mathrm{GeV}$.

For a light Z' ($M_{Z'} < M_Z$) direct searches in e^+e^- colliders have ruled out any Z' unless it has extremely weak couplings to leptons. For a combined analysis of the various pre-LEP experiments see Ref. 8.

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MASS LIMITS for Z' (Heavy Neutral Vector Boson Other Than Z)

Limits for Z'_{SM}

Z'_{SM} is assumed to have couplings with quarks and leptons which are identical to those of Z.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>690	95	[38] ABE	97S	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$, $\mu^+\mu^-$
>779	95	[39,40] LANGACKER	92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>490	95	ABACHI	96D	D0	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>505	95	[41] ABE	95	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>398	95	[42] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>237	90	[43] ALITTI	93	UA2	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
>119	90	[44] ALLEN	93	CALO	$\nu e \rightarrow \nu e$
none 490–560	95	[45] RIZZO	93	RVUE	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
>412	95	ABE	92B	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$, $\mu^+\mu^-$
>387	95	[46] ABE	91D	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>307	90	[47] GEIREGAT	91	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>426	90	[48] ABE	90F	VNS	e^+e^-
>208	90	[49] HAGIWARA	90	RVUE	e^+e^-
>173	90	[50] ALBAJAR	89	UA1	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>180	90	[51] ANSARI	87D	UA2	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>160	90	[52] ARNISON	86B	UA1	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$

[38] ABE 97S limit is obtained assuming that Z' decays to known fermions only.

[39] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t > 89$ GeV used.

[40] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0086 < \theta < 0.0005$.

[41] ABE 95 limit is obtained assuming that Z' decays to known fermions only.

[42] VILAIN 94B assume $m_t = 150$ GeV.

[43] ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes $B(Z' \rightarrow q\overline{q})=0.7$. See their Fig. 5 for limits in the $m_{Z'}$–$B(q\overline{q})$ plane.

[44] ALLEN 93 limit is from total cross section for $\nu e \rightarrow \nu e$, where $\nu = \nu_e, \nu_\mu, \overline{\nu}_\mu$.

[45] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[46] ABE 91D give $\sigma(Z')\cdot B(e^+e^-) < 1.31$ pb (95%CL) for $m_{Z'} > 200$ GeV at $E_{cm} = 1.8$ TeV. Limits ranging from 2 to 30 pb are given for $m_{Z'} = 100$–200 GeV.

[47] GEIREGAT 91 limit is from comparison of g_V^e from $\nu_\mu e$ scattering with $\Gamma(Z \rightarrow ee)$ from LEP. Zero mixing assumed.

[48] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. They fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[49] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[50] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(Z')\ B(ee) < 4.2$ pb (90% CL).

[51] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{Z'}$–$[(g_{Z'q})^2\ B(Z' \rightarrow e^+e^-)]$ plane. Note that the quantity $(g_{Z'q})^2 B(Z' \rightarrow e^+e^-)$ is normalized to unity for the standard Z couplings.

[52] ARNISON 86B find no excess e^+e^- pairs among 13 pairs from Z. Set limit $\sigma \times B(e^+e^-) < 13$ pb at CL = 90% at $E_{cm} = 546$ and 630 GeV.

Limits for Z_{LR}

Z_{LR} is the extra neutral boson in left-right symmetric models. $g_L = g_R$ is assumed unless noted. Values in parentheses assume stronger constraint on the Higgs sector, usually motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>630	95	[53] ABE	97S	CDF	$p\overline{p}$; $Z'_{LR} \rightarrow e^+e^-$, $\mu^+\mu^-$
>389	95	[54,55] LANGACKER	92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>190	95	[56] BARATE	97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>445	95	[57] ABE	95	CDF	$p\overline{p}$; $Z'_{LR} \rightarrow e^+e^-$
>253	95	[58] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>130	95	[59] ADRIANI	93D	L3	Z parameters
(> 1500)	90	[60] ALTARELLI	93B	RVUE	Z parameters
none 490–560	95	[61] RIZZO	93	RVUE	$p\overline{p}$; $Z_{LR} \rightarrow q\overline{q}$
>310	95	[62] ABE	92B	CDF	$p\overline{p}$
>230	95	[63] ABE	92B	CDF	$p\overline{p}$
(> 900)	90	[64] DELAGUILA	92	RVUE	
(> 1400)		[65] LAYSSAC	92B	RVUE	Z parameters
(> 564)	90	[66] POLAK	92	RVUE	μ decay
>474	90	[67] POLAK	92B	RVUE	Electroweak
(> 1340)		[68] RENTON	92	RVUE	
(> 800)	90	[69] ALTARELLI	91B	RVUE	Z parameters
(> 795)	90	[70] DELAGUILA	91	RVUE	
>382	90	[71] POLAK	91	RVUE	Electroweak
[> 2000]		WALKER	91	COSM	Nucleosynthesis; light ν_R
[> 500]		[72] GRIFOLS	90	ASTR	SN 1987A; light ν_R
(> 460)	90	[73] HE	90B	RVUE	
[> 2400–6800]		[74] BARBIERI	89B	ASTR	SN 1987A; light ν_R
>189		[75] DELAGUILA	89	RVUE	$p\overline{p}$
[> 10000]		RAFFELT	88	ASTR	SN 1987A; light ν_R
>325	90	[76] AMALDI	87	RVUE	
>278	90	[77] DURKIN	86	RVUE	
>150	95	[78] ADEVA	85B	MRKJ	$e^+e^- \rightarrow \mu^+\mu^-$

[53] ABE 97S limit is obtained assuming that Z' decays to known fermions only.

[54] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t > 89$ GeV used.

[55] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0025 < \theta < 0.0083$.

[56] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0017 < \theta < 0.0035$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+120}_{-90}$ GeV. See their Fig. 4 for the limit contour in the mass-mixing plane.

[57] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[58] VILAIN 94B assume $m_t = 150$ GeV and $\theta=0$. See Fig. 2 for limit contours in the mass-mixing plane.

[59] ADRIANI 93D give limits on the Z-Z' mixing $-0.002 < \theta < 0.015$ assuming the ABE 92B mass limit.

[60] ALTARELLI 93B limit is from LEP data available in summer '93 and is for $m_t = 110$ GeV. $m_H = 100$ GeV and $\alpha_s = 0.118$ assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in Table 4.

[61] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[62] These limits assume that Z' decays to known fermions only.

[63] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[64] See Fig. 7b and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[65] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[66] POLAK 92 limit is from $m_{W_R} > 477$ GeV, which is derived from muon decay parameters assuming light ν_R. Specific Higgs sector is assumed.

[67] POLAK 92B limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using Z parameters, m_W, and low-energy neutral current data as of 1991. Light ν_R assumed and $m_t = m_H = 100$ GeV used. Supersedes POLAK 91.

[68] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[69] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m_t > 90$ GeV and $m_{H^0} < 1$ TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[70] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with $m_Z = 91.10 \pm 0.04$ GeV, $m_t > 77$ GeV, $m_{H^0} < 1$ TeV assumed.

[71] POLAK 91 limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using m_W, m_Z, and low-energy neutral current data as of 1990. Light ν_R assumed and $m_t = m_H = 100$ GeV used. Superseded by POLAK 92B.

[72] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim 1$ MeV. See also GRIFOLS 90D, RIZZO 91.

[73] HE 90B model assumes a specific Higgs sector. Neutral current data of COSTA 88 as well as m_Z is used. g_R is left free in the fit.

[74] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[75] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[76] A wide range of neutral current data as of 1986 are used in the fit.

[77] A wide range of neutral current data as of 1985 are used in the fit.

[78] ADEVA 85B measure asymmetry of μ-pair production, following formalism of RIZZO 81.

Limits for Z_χ

Z_χ is the extra neutral boson in SO(10) → SU(5) × $U(1)_\chi$. $g_\chi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>595	95	[79] ABE 97S	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
>321	95	[80,81] LANGACKER 92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>190	95	[82] ARIMA 97	VNS	Bhabha scattering
>236	95	[83] BARATE 97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>196	95	[84] BUSKULIC 96N	ALEP	Hadronic cross section
>425	95	[85] ABE 95	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-$
>147	95	[86] ABREU 95M	DLPH	Z parameters and $e^+e^- \rightarrow \mu^+\mu^-(n\gamma)$
		[87] NARDI 95	RVUE	Z parameters
		[88] BUSKULIC 94	ALEP	Z parameters
>262	95	[89] VILAIN 94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>117	95	[90] ADRIANI 93D	L3	Z parameters
(>900)	90	[91] ALTARELLI 93B	RVUE	Z parameters
>340	95	[92] ABE 92B	CDF	$p\overline{p}$
>280	95	[93] ABE 92B	CDF	$p\overline{p}$
(>650)	90	[94] DELAGUILA 92	RVUE	
(>760)		[95] LAYSSAC 92B	RVUE	Z parameters
>148	95	[96] LEIKE 92	RVUE	Z parameters
(>700)		[97] RENTON 92	RVUE	
(> 500)	90	[98] ALTARELLI 91B	RVUE	Z parameters
(> 570)		[99] BUCHMUEL... 91	RVUE	Z parameters
(> 555)	90	[100] DELAGUILA 91	RVUE	
[>1470]		[101] FARAGGI 91	COSM	Nucleosynthesis; light ν_R
>320	90	[102] GONZALEZ-G..91	RVUE	
>221		[103] MAHANTHAP..91	RVUE	Cs
>231	90	[104,105] ABE 90F	VNS	e^+e^-
>206	90	[105,106] ABE 90F	RVUE	e^+e^-, $\nu_\mu e$
>335		[107] BARGER 90B	RVUE	$p\overline{p}$
(> 650)	90	[108] GLASHOW 90	RVUE	
[> 1140]		[109] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[> 2100]		[110] GRIFOLS 90	ASTR	SN 1987A; light ν_R
none <150 or > 363	90	[111] HAGIWARA 90	RVUE	e^+e^-
>177		[112] DELAGUILA 89	RVUE	$p\overline{p}$
>280	95	[113] DORENBOS... 89	CHRM	$g_\chi = g_Z$
>352	90	[114] COSTA 88	RVUE	
>170	90	[115] ELLIS 88	RVUE	$p\overline{p}$
>273	90	[114] AMALDI 87	RVUE	
>266	90	[116] MARCIANO 87	RVUE	
>283	90	[117] DURKIN 86	RVUE	

[79] ABE 97S limit is obtained assuming that Z' decays to known fermions only.

[80] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[81] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0048 < \theta < 0.0097$.

[82] Z-Z' mixing is assumed to be zero.

[83] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0016 < \theta < 0.0036$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+120}_{-90}$ GeV. See their Fig. 4 for the limit contour in the mass-mixing plane.

[84] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

[85] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[86] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[87] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0032 < \theta < 0.0031$ for $M_{Z'}$ >500 GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0032 < \theta < 0.0079$.

[88] BUSKULIC 94 give 95%CL limits on the Z-Z' mixing $-0.0091 < \theta < 0.0023$.

[89] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[90] ADRIANI 93D give limits on the Z-Z' mixing $-0.004 < \theta < 0.015$ assuming the ABE 92B mass limit.

[91] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in their Fig. 2.

[92] These limits assume that Z' decays to known fermions only.

[93] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[94] See Fig. 7a and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[95] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[96] LEIKE 92 is based on '90 LEP data published in LEP 92.

[97] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[98] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. m_t > 90 GeV and m_{H^0} < 1 TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[99] BUCHMUELLER 91 limit is from LEP data. Specific assumption is made for the Higgs sector.

[100] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with $m_Z = 91.10 \pm 0.04$ GeV, m_t > 77 GeV, m_{H^0} < 1 TeV assumed.

[101] FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos $\Delta N_\nu < 0.5$ and is valid for $m_{\nu_R} < 1$ MeV.

[102] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, Z mass and widths, m_W from ABE 90G. 100 $< m_t <$ 200 GeV, m_{H^0} = 100 GeV assumed. Dependence on m_t is shown in Fig. 7.

[103] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with m_W, m_Z.

[104] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[105] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[106] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[107] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[108] GLASHOW 90 model assumes a specific Higgs sector. See GLASHOW 90B.

[109] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[110] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

[111] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries. The upper mass limit disappears at 2.7 s.d.

[112] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[113] DORENBOSCH 89 obtain the limit $(g_\chi/g_Z)^2 \cdot (m_Z/m_{Z_\chi})^2 < 0.11$ at 95% CL from the processes $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ and $\nu_\mu e \rightarrow \nu_\mu e$.

[114] A wide range of neutral current data as of 1986 are used in the fit.

[115] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

[116] MARCIANO 87 limit from unitarity of Cabibbo-Kobayashi-Maskawa matrix.

[117] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_ψ

Z_ψ is the extra neutral boson in E_6 → SO(10) × $U(1)_\psi$. $g_\psi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>590	95	[118] ABE 97S	CDF	$p\overline{p}$; $Z'_\psi \rightarrow e^+e^-, \mu^+\mu^-$
>160	95	[119,120] LANGACKER 92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>160	95	[121] BARATE 97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>148	95	[122] BUSKULIC 96N	ALEP	Hadronic cross section
>415	95	[123] ABE 95	CDF	$p\overline{p}$; $Z'_\psi \rightarrow e^+e^-$
>105	95	[124] ABREU 95M	DLPH	Z parameters and $e^+e^- \rightarrow \mu^+\mu^-(n\gamma)$
		[125] NARDI 95	RVUE	Z parameters
>135	95	[126] VILAIN 94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>118	95	[127] ADRIANI 93D	L3	Z parameters
>320	95	[128] ABE 92B	CDF	$p\overline{p}$
>180	95	[129] ABE 92B	CDF	$p\overline{p}$
>122	95	[130] LEIKE 92	RVUE	Z parameters
>105	90	[131,132] ABE 90F	VNS	e^+e^-
>146	90	[132,133] ABE 90F	RVUE	e^+e^-, $\nu_\mu e$
>320		[134] BARGER 90B	RVUE	$p\overline{p}$
[> 160]		[135] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[> 2000]		[136] GRIFOLS 90D	ASTR	SN 1987A; light ν_R
>136	90	[137] HAGIWARA 90	RVUE	e^+e^-
>154	90	[138] AMALDI 87	RVUE	
>146	90	[139] DURKIN 86	RVUE	

[118] ABE 97S limit is obtained assuming that Z' decays to known fermions only.

[119] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[120] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0025 < \theta < 0.013$.

[121] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0020 < \theta < 0.0038$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+120}_{-90}$ GeV. See their Fig. 4 for the limit contour in the mass-mixing plane.

[122] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

[123] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[124] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[125] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0056 < \theta < 0.0055$ for $M_{Z'}$ >500 GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0066 < \theta < 0.0071$.

[126] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[127] ADRIANI 93D give limits on the Z-Z' mixing $-0.003 < \theta < 0.020$ assuming the ABE 92B mass limit.

[128] These limits assume that Z' decays to known fermions only.

[129] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[130] LEIKE 92 is based on '90 LEP data published in LEP 92.

[131] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[132] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[133] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[134] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[135] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[136] GRIFOLS 90D limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also RIZZO 91.

[137] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[138] A wide range of neutral current data as of 1986 are used in the fit.

[139] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_η

Z_η is the extra neutral boson in E_6 models, corresponding to $Q_\eta = \sqrt{3/8}\, Q_\chi - \sqrt{5/8}\, Q_\psi$. $g_\eta = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho=1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>620	95	[140] ABE	97S	CDF	$p\overline{p}$; $Z'_\eta \rightarrow e^+e^-, \mu^+\mu^-$
>182	95	[141,142] LANGACKER	92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>173	95	[143] BARATE	97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>167	95	[144] BUSKULIC	96N	ALEP	Hadronic cross section
>440	95	[145] ABE	95	CDF	$p\overline{p}$; $Z'_\eta \rightarrow e^+e^-$
>109	95	[146] ABREU	95M	DLPH	Z parameters and $e^+e^- \rightarrow \mu^+\mu^-(n\gamma)$
		[147] NARDI	95	RVUE	Z parameters
>100	95	[148] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>100	95	[149] ADRIANI	93D	L3	Z parameters
(>500)	90	[150] ALTARELLI	93B	RVUE	Z parameters
>340	95	[151] ABE	92B	CDF	$p\overline{p}$
>230	95	[152] ABE	92B	CDF	$p\overline{p}$
(>450)	90	[153] DELAGUILA	92	RVUE	
(>315)		[154] LAYSSAC	92B	RVUE	Z parameters
>118	95	[155] LEIKE	92	RVUE	Z parameters
(>470)		[156] RENTON	92	RVUE	
(> 300)	90	[157] ALTARELLI	91B	RVUE	Z parameters
>120	90	[158] GONZALEZ-G..	91	RVUE	
>125	90	[159,160] ABE	90F	VNS	e^+e^-
>115	90	[160,161] ABE	90F	RVUE	e^+e^-, $\nu_\mu e$
>340		[162] BARGER	90B	RVUE	$p\overline{p}$
[> 820]		[163] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 3300]		[164] GRIFOLS	90	ASTR	SN 1987A; light ν_R
>100	90	[165] HAGIWARA	90	RVUE	e^+e^-
[> 1040]		[163] LOPEZ	90	COSM	Nucleosynthesis; light ν_R
>173		[166] DELAGUILA	89	RVUE	$p\overline{p}$
>129	90	[167] COSTA	88	RVUE	
>156	90	[168] ELLIS	88	RVUE	
>167	90	[169] ELLIS	88	RVUE	$p\overline{p}$
>111	90	[167] AMALDI	87	RVUE	
>143	90	[170] BARGER	86B	RVUE	$p\overline{p}$
>130	90	[171] DURKIN	86	RVUE	
[> 760]		[163] ELLIS	86	COSM	Nucleosynthesis; light ν_R
[> 500]		[163] STEIGMAN	86	COSM	Nucleosynthesis; light ν_R

[140] ABE 97S limit is obtained assuming that Z' decays to known fermions only.

[141] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[142] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.038 < \theta < 0.002$.

[143] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.021 < \theta < 0.012$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+120}_{-90}$ GeV. See their Fig. 4 for the limit contour in the mass-mixing plane.

[144] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

[145] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[146] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[147] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0087 < \theta < 0.0075$ for $M_{Z'}$ >500 GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0087 < \theta < 0.010$.

[148] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[149] ADRIANI 93D give limits on the Z-Z' mixing $-0.029 < \theta < 0.010$ assuming the ABE 92B mass limit.

[150] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The 90%CL limit on the Z-Z' mixing angle is in Fig. 2.

[151] These limits assume that Z' decays to known fermions only.

[152] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[153] See Fig. 7d in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane from electroweak fit including '90 LEP data.

[154] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[155] LEIKE 92 is based on '90 LEP data published in LEP 92.

[156] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[157] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. m_t > 90 GeV and m_{H^0} < 1 TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[158] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, LEP Z mass and widths, m_W from ABE 90G. 100 $< m_t <$ 200 GeV, m_{H^0} = 100 GeV assumed. Dependence on m_t is shown in Fig. 8.

[159] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[160] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[161] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[162] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[163] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[164] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

[165] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[166] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[167] A wide range of neutral current data as of 1986 are used in the fit.

[168] Z_η mass limits obtained by combining constraints from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider and the global analysis of neutral current data by COSTA 88. Least favorable spectrum of three (E_6 27) generations of particles and their superpartners are assumed.

[169] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

[170] BARGER 86B limit is based on UA1/UA2 limit on $p\overline{p} \rightarrow Z'$, $Z' \rightarrow e^+e^-$ (Lepton Photon Symp., Kyoto, '85). Extra decay channels for Z' are assumed not be open.

[171] A wide range of neutral current data as of 1985 are used in the fit.

Limits for other Z'

$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[172] DELAGUILA	92	RVUE	
>360		[173] ALTARELLI	91	RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
>190		[174] MAHANTHAP..	91	RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
		[175] GRIFOLS	90C	RVUE	
		[176] DELAGUILA	89	RVUE	$p\overline{p}$
>180	90	[177,178] COSTA	88	RVUE	Z_β with $\tan\beta = \sqrt{15}$
>158	90	[179] ELLIS	88	RVUE	Z_β ($\tan\beta = \sqrt{15}$), $p\overline{p}$

[172] Fig. 7c and 7e in DELAGUILA 92 give limits for $\tan\beta = -1/\sqrt{15}$ and $\sqrt{15}$ from electroweak fit including '90 LEP data.

[173] ALTARELLI 91 limit is from atomic parity violation in Cs together with LEP, CDF data. Z-Z' mixing is assumed to be zero to set the limit.

[174] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with m_W, m_Z. See Table III of MAHANTHAPPA 91 (corrected in erratum) for limits on various Z' models.

[175] GRIFOLS 90C obtains a limit for Z' mass as a function of mixing angle β (his $\theta = \beta - \pi/2$), which is derived from a LAMPF experiment on $\sigma(\nu_e e)$ (ALLEN 90). The result is shown in Fig. 1.

[176] See Table I of DELAGUILA 89 for limits on various Z' models.

[177] $g_\beta = e/\cos\theta_W$ and ρ = 1 assumed.

[178] A wide range of neutral current data as of 1986 are used in the fit.

[179] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

LEPTOQUARK QUANTUM NUMBERS

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Leptoquarks are particles carrying both baryon number (B) and lepton number (L). They are expected to exist in various extensions of the Standard Model (SM). The possible quantum numbers of leptoquark states can be restricted by assuming that their direct interactions with the ordinary SM fermions are dimensionless and invariant under the SM gauge group. Table 1 shows the list of all possible quantum numbers with this assumption [1]. The columns of $\mathrm{SU}(3)_C$, $\mathrm{SU}(2)_W$, and $\mathrm{U}(1)_Y$ in Table 1 indicate the QCD representation, the weak isospin representation, and the weak hypercharge, respectively. Naming conventions of leptoquark states are taken from Ref. 1. The spin of a leptoquark state is taken to be 1 (vector leptoquark) or 0 (scalar leptoquark).

Table 1: Possible leptoquarks and their quantum numbers.

Leptoquarks	Spin	$3B+L$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_W$	$\mathrm{U}(1)_Y$
S_1	0	−2	$\bar{3}$	1	1/3
$\tilde{S}_1$	0	−2	$\bar{3}$	1	4/3
S_3	0	−2	$\bar{3}$	3	1/3
V_2	1	−2	$\bar{3}$	2	5/6
$\tilde{V}_2$	1	−2	$\bar{3}$	2	−1/6
R_2	0	0	3	2	7/6
$\tilde{R}_2$	0	0	3	2	1/6
U_1	1	0	3	1	2/3
$\tilde{U}_1$	1	0	3	1	5/3
U_3	1	0	3	3	2/3

If we do not require leptoquark states to couple directly with SM fermions, different assignments of quantum numbers become possible.

The Pati-Salam model [2] is an example predicting the existence of a leptoquark state. In this model a vector leptoquark appears at the scale where the Pati-Salam SU(4) "color" gauge group breaks into the familiar QCD $\mathrm{SU}(3)_C$ group (or $\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L}$). The Pati-Salam leptoquark is a weak isosinglet and its hypercharge is 2/3 (U_1 leptoquark in Table 1). The coupling strength of the Pati-Salam leptoquark is given by the QCD coupling at the Pati-Salam symmetry breaking scale.

Bounds on leptoquark states are obtained both directly and indirectly. Direct limits are from their production cross sections at colliders, while indirect limits are calculated from the bounds on the leptoquark induced four-fermion interactions which are obtained from low energy experiments.

The pair production cross sections of leptoquarks are evaluated from their interactions with gauge bosons. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 1. The magnetic-dipole-type and the electric-quadrupole-type interactions of a vector leptoquark are, however, not determined even if we fix its gauge quantum numbers as listed in the table [3]. We need extra assumptions about these interactions to evaluate the pair production cross section for a vector leptoquark.

If a leptoquark couples to fermions of more than a single generation in the mass eigenbasis of the SM fermions, it can induce four-fermion interactions causing flavor-changing-neutral-currents and lepton-family-number violations. Non-chiral leptoquarks, which couple simultaneously to both left- and right-handed quarks, cause four-fermion interactions affecting the $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio [4]. Indirect limits provide stringent constraints on these leptoquarks. Since the Pati-Salam leptoquark has non-chiral coupling with both e and μ, indirect limits from the bounds on $K_L \to \mu e$ lead to severe bounds on the Pati-Salam leptoquark mass. For detailed bounds obtained in this way, see the Boson Particle Listings for "Indirect Limits for Leptoquarks" and its references.

It is therefore often assumed that a leptoquark state couples only to a single generation in a chiral interaction, where indirect limits become much weaker. This assumption gives strong constraints on concrete models of leptoquarks, however. Leptoquark states which couple only to left- or right-handed quarks are called chiral leptoquarks. Leptoquark states which couple only to the first (second, third) generation are referred as the first (second, third) generation leptoquarks in this section.

Reference

1. W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. **B191**, 442 (1987).
2. J.C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974).
3. J. Blümlein, E. Boos, and A. Kryukov, Z. Phys. **C76**, 137 (1997).
4. O. Shanker, Nucl. Phys. **B204**, 375 (1982).

MASS LIMITS for Leptoquarks from Pair Production

These limits rely only on the color or electroweak charge of the leptoquark.

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
>225	95		[180] ABBOTT 98E	D0	First generation
> 99	95		[181] ABE 97F	CDF	Third generation
>131	95		[182] ABE 95U	CDF	Second generation
> 45.5	95		[183,184] ABREU 93J	DLPH	First + second generation
> 44.4	95		[185] ADRIANI 93M	L3	First generation
> 44.6	95		[186] ADRIANI 93M	L3	Third generation
> 44	95		[185] DECAMP 92	ALEP	First or second generation
> 45	95		[185] DECAMP 92	ALEP	Third generation
> 44.2	95		[185] ALEXANDER 91	OPAL	First or second generation
> 41.4	95		[185] ALEXANDER 91	OPAL	Third generation

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
>225	95		[187] ABBOTT 97B	D0	Result included in ABBOTT 98E
>213	95		[187] ABE 97X	CDF	First generation
>119	95		[188] ABACHI 95G	D0	Second generation
>116	95		[189] ABACHI 94B	D0	First generation
> 80	95		[190] ABE 93I	CDF	First generation
> 44.5	95		[185] ADRIANI 93M	L3	Second generation
> 42.1	95		[191] ABREU 92F	DLPH	Second generation
> 74	95		[192] ALITTI 92E	UA2	First generation
> 43.2	95		[185] ADEVA 91B	L3	First generation
> 43.4	95		[185] ADEVA 91B	L3	Second generation
none 8.9–22.6	95		[193] KIM 90	AMY	First generation
none 10.2–23.2	95		[193] KIM 90	AMY	Second generation
none 5–20.8	95		[194] BARTEL 87B	JADE	
none 7–20.5	95	2	[195] BEHREND 86B	CELL	

[180] ABBOTT 98E search for scalar leptoquarks using $e\nu jj$, $eejj$, and $\nu\nu jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit above assumes B(eq)=1. For B(eq)=0.5 and 0, the bound becomes 204 and 79 GeV, respectively.

[181] ABE 97F search for third generation scalar and vector leptoquarks in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The quoted limit is for scalar leptoquark with B(τb) = 1.

[182] ABE 95U search for scalar leptoquarks of charge Q=2/3 and −1/3 using $\mu\mu jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit is for B(μq) = 1. For B(μq) = B(νq) = 0.5, the limit is > 96 GeV.

[183] Limit is for charge −1/3 isospin-0 leptoquark with B(ℓq) = 2/3.

[184] First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.

[185] Limits are for charge −1/3, isospin-0 scalar leptoquarks decaying to $\ell^- q$ or νq with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.

[186] ADRIANI 93M limit for charge −1/3, isospin-0 leptoquark decaying to τb.

[187] ABBOTT 97B, ABE 97X search for scalar leptoquarks using $eejj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit is for B(eq)=1.

[188] ABACHI 95G search for scalar leptoquarks using $\mu\mu$+jets and $\mu\nu_\mu$+jets events in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The limit is for B(μq) = 1. For B(μq) = B(νq) = 0.5, the limit is > 97 GeV.

[189] ABACHI 94B search for $eejj$ and $e\nu jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. ABACHI 94B obtain the limit >120 GeV for B(eq)=B(νq)=0.5 and >133 GeV for B(eq)=1. A change in the D0 luminosity monitor constant reduces the first bound to >116 GeV quoted above (see FERMILAB-TM-1911). This limit does not depend on the electroweak quantum numbers of the leptoquark.

[190] ABE 93I search for $\ell\ell jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit is for B(eq) = B(νq) = 0.5 and improves to >113 GeV for B(eq) = 1. This limit does not depend on electroweak quantum numbers of the leptoquark.

[191] ABREU 92F limit is for charge −1/3 isosin-0 leptoquark with B(μq)=2/3. If first and second generation leptoquarks are degenerate, the limit is 43.0 GeV, and for a charge 2/3 second generation leptoquark 43.4 GeV. Cross-section limit for pair production of states decaying to ℓq is given in the paper.

[192] ALITTI 92E search for $\ell\ell jj$ and $\ell\nu jj$ events in $p\overline{p}$ collisions at E_{cm}=630 GeV. The limit is for B(eq) = 1 and is reduced to 67 GeV for B(eq) = B(νq) = 0.5. This limit does not depend on electroweak quantum numbers of the leptoquark.

[193] KIM 90 assume pair production of charge 2/3 scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of de^+ and $u\overline{\nu}$ ($s\mu^+$ and $c\overline{\nu}$). See paper for limits for specific branching ratios.

[194] BARTEL 87B limit is valid when a pair of charge 2/3 spinless leptoquarks X is produced with point coupling, and when they decay under the constraint B(X → $c\overline{\nu}_\mu$) + B(X → $s\mu^+$) = 1.

[195] BEHREND 86B assumed that a charge 2/3 spinless leptoquark, χ, decays either into $s\mu^+$ or $c\overline{\nu}$: B($\chi \rightarrow s\mu^+$) + B($\chi \rightarrow c\overline{\nu}$) = 1.

MASS LIMITS for Leptoquarks from Single Production

These limits depend on the q-ℓ-leptoquark coupling g_{LQ}. It is often assumed that $g^2_{LQ}/4\pi$=1/137. Limits shown are for a scalar, weak isoscalar, charge −1/3 leptoquark.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>237	95	[196] AID 96B	H1	First generation
> 73	95	[197] ABREU 93J	DLPH	Second generation
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[198] DERRICK 97	ZEUS	Lepton-flavor violation
>230	95	[199] AHMED 94B	H1	Sup. by AID 96B
> 65	95	[197] ABREU 93J	DLPH	First generation
>181	95	[200] ABT 93	H1	First generation
>168	95	[201] DERRICK 93	ZEUS	First generation

[196] The quoted limit is for a left-handed scalar leptoquark which solely couples to the first generation with electromagnetic strength. AID 96B also search for leptoquarks with lepton-flavor violating couplings. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Fig. 2, Fig. 3, and Table 2. AID 96B supersedes AHMED 94B.

[197] Limit from single production in Z decay. The limit is for a leptoquark coupling of electromagnetic strength and assumes B(ℓq) = 2/3. The limit is 77 GeV if first and second leptoquarks are degenerate.

[198] DERRICK 97 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 5–8 and Table 1 for detailed limits.

[199] AHMED 94B limit is for the left-handed leptoquark decaying to eq and νq with B(eq) = B(νq)=1/2. Electromagnetic coupling strength is assumed for the scalar leptoquark interaction. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Table 2 and Fig. 6.

[200] ABT 93 search for single leptoquark production in ep collisions with the decays eq and νq. The limit is for a leptoquark coupling of electromagnetic strength and assumes B(eq) = B(νq) = 1/2. The limit for B(eq) = 1 is 178 GeV. For limits on states with different quantum numbers, see their Fig. 2. ABT 93 superseded by AHMED 94B.

[201] DERRICK 93 search for single leptoquark production in ep collisions with the decay eq and νq. The limit is for leptoquark coupling of electromagnetic strength and assumes B(eq) = B(νq) = 1/2. The limit for B(eq) = 1 is 176 GeV. For limits on states with different quantum numbers, see their Table 3.

Indirect Limits for Leptoquarks

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 0.76	95	[202] DEANDREA 97	RVUE	$\tilde{R}_2$ leptoquark
		[203] DERRICK 97	ZEUS	Lepton-flavor violation
		[204] GROSSMAN 97	RVUE	$B \rightarrow \tau^+\tau^-$ (X)
		[205] JADACH 97	RVUE	$e^+e^- \rightarrow q\overline{q}$
> 0.31	95	[206] AID 95	H1	First generation
>1200		[207] KUZNETSOV 95B	RVUE	Pati-Salam type
		[208] MIZUKOSHI 95	RVUE	Third generation scalar leptoquark
> 0.3	95	[209] BHATTACH... 94	RVUE	Spin-0 leptoquark coupled to $\overline{e}_R t_L$
		[210] DAVIDSON 94	RVUE	
> 18		[211] KUZNETSOV 94	RVUE	Pati-Salam type
> 0.43	95	[212] LEURER 94	RVUE	First generation spin-1 leptoquark
> 0.44	95	[212] LEURER 94B	RVUE	First generation spin-0 leptoquark
		[213] MAHANTA 94	RVUE	P and T violation
> 350		[214] DESHPANDE 83	RVUE	Sup. by KUZNETSOV 95B
> 1		[215] SHANKER 82	RVUE	Nonchiral spin-0 leptoquark
> 125		[215] SHANKER 82	RVUE	Nonchiral spin-1 leptoquark

[202] DEANDREA 97 limit is for $\tilde{R}_2$ leptoquark obtained from atomic parity violation (APV). The coupling of leptoquark is assumed to be electromagnetic strength. See Table 2 for limits of the four-fermion interactions induced by various scalar leptoquark exchange. DEANDREA 97 combines APV limit and limits from Tevatron and HERA. See Fig. 1–4 for combined limits of leptoquark in mass-coupling plane.

[203] DERRICK 97 search for lepton-flavor violation in ep collision. See their Tables 2–5 for limits on lepton-flavor violating four-fermion interactions induced by various leptoquarks.

[204] GROSSMAN 97 estimate the upper bounds on the branching fraction $B \rightarrow \tau^+\tau^-$ (X) from the absence of the B decay with large missing energy. These bounds can be used to constrain leptoquark induced four-fermion interactions.

[205] JADACH 97 limit is from $e^+e^- \rightarrow q\overline{q}$ cross section at $\sqrt{s}$=172.3 GeV which can be affected by the t- and u-channel exchanges of leptoquarks. See their Fig. 1 for limits on vector leptoquarks in mass-coupling plane.

[206] AID 95 limit is for the weak isotriplet spin-1 leptoquark with the electromagnetic coupling strength. For the limits of leptoquarks with different quantum number, see their Table 2. AID 95 limits are from the measurements of the Q^2 spectrum measurement of $ep \rightarrow eX$.

[207] KUZNETSOV 95B use π, K, B, τ decays and μe conversion and give a list of bounds on the leptoquark mass and the fermion mixing matrix in the Pati-Salam model. The quoted limit is from $K_L \rightarrow \mu e$ decay assuming zero mixing. See also KUZNETSOV 94, DESHPANDE 83, and DIMOPOULOS 81.

[208] MIZUKOSHI 95 calculate the one-loop radiative correction to the Z-physics parameters in various scalar leptoquark models. See their Fig. 4 for the exclusion plot of third generation leptoquark models in mass-coupling plane.

[209] BHATTACHARYYA 94 limit is from one-loop radiative correction to the leptonic decay width of the Z. m_H=250 GeV, $\alpha_s(m_Z)$=0.12, m_t=180 GeV, and the electroweak strength of leptoquark coupling are assumed. For leptoquark coupled to $\overline{e}_L t_R$, $\overline{\mu}t$, and $\overline{\tau}t$, see Fig. 2 in BHATTACHARYYA 94B erratum and Fig. 3.

[210] DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion insteractions from π, K, D, B, μ, τ decays and meson mixings, *etc.* See Table 15 of DAVIDSON 94 for detail.

[211] KUZNETSOV 94 gives mixing independent bound of the Pati-Salam leptoquark from the cosmological limit on $\pi^0 \rightarrow \overline{\nu}\nu$.

[212] LEURER 94, LEURER 94B limits are obtained from atomic parity violation and apply to any chiral leptoquark which couples to the first generation with electromagnetic strength. For a nonchiral leptoquark, universality in $\pi_{\ell 2}$ decay provides a much more stringent bound. See also SHANKER 82.

[213] MAHANTA 94 gives bounds of P- and T-violating scalar-leptoquark couplings from atomic and molecular experiments.

[214] DESHPANDE 83 used upper limit on $K^0_L \rightarrow \mu e$ decay with renormalization-group equations to estimate coupling at the heavy boson mass. See also DIMOPOULOS 81.

[215] From ($\pi \rightarrow e\nu$)/($\pi \rightarrow \mu\nu$) ratio. SHANKER 82 assumes the leptoquark induced four-fermion coupling $4g^2/M^2$ ($\overline{\nu}_{eL}\, u_R$) ($\overline{d}_L\, e_R$)with g=0.004 for spin-0 leptoquark and g^2/M^2 ($\overline{\nu}_{eL}\, \gamma_\mu u_L$) ($\overline{d}_R\, \gamma^\mu e_R$) with $g \simeq$ 0.6 for spin-1 leptoquark.

MASS LIMITS for Diquarks

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 290–420	95	[216] ABE 97G	CDF	E_6 diquark
none 15–31.7	95	[217] ABREU 94O	DLPH	SUSY E_6 diquark

[216] ABE 97G search for new particle decaying to dijets.

[217] ABREU 94O limit is from $e^+e^- \rightarrow \overline{c}\overline{s}cs$. Range extends up to 43 GeV if diquarks are degenerate in mass.

MASS LIMITS for g_A (axigluon)

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling to quarks with the same coupling strength as gluons.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 200–980	95	[218] ABE 97G	CDF	$p\overline{p} \rightarrow g_A X$, X → 2 jets
none 200–870	95	[219] ABE 95N	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow q\overline{q}$
none 240–640	95	[220] ABE 93G	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
>50	95	[221] CUYPERS 91	RVUE	$\sigma(e^+e^- \rightarrow$ hadrons)
none 120–210	95	[222] ABE 90H	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
>29		[223] ROBINETT 89	THEO	Partial-wave unitarity
none 150–310	95	[224] ALBAJAR 88B	UA1	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
>20		BERGSTROM 88	RVUE	$p\overline{p} \rightarrow \Upsilon X$ via $g_A g$
> 9		[225] CUYPERS 88	RVUE	Υ decay
>25		[226] DONCHESKI 88B	RVUE	Υ decay

[218] ABE 97G search for new particle decaying to dijets.

[219] ABE 95N assume axigluons decaying to quarks in the Standard Model only.

[220] ABE 93G assume $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 10$.

[221] CUYPERS 91 compare α_s measured in Υ decay and that from R at PEP/PETRA energies.

[222] ABE 90H assumes $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 5\,(\Gamma(g_A) = 0.09 m_{g_A})$. For $N = 10$, the excluded region is reduced to 120–150 GeV.

[223] ROBINETT 89 result demands partial-wave unitarity of $J = 0$ $t\bar{t} \rightarrow t\bar{t}$ scattering amplitude and derives a limit $m_{g_A} > 0.5\ m_t$. Assumes $m_t > 56$ GeV.

[224] ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution. $\Gamma(g_A) < 0.4\ m_{g_A}$ assumed. See also BAGGER 88.

[225] CUYPERS 88 requires $\Gamma(\Upsilon \rightarrow g g_A) < \Gamma(\Upsilon \rightarrow g g g)$. A similar result is obtained by DONCHESKI 88.

[226] DONCHESKI 88B requires $\Gamma(\Upsilon \rightarrow g q\bar{q})/\Gamma(\Upsilon \rightarrow g g g) < 0.25$, where the former decay proceeds via axigluon exchange. A more conservative estimate of < 0.5 leads to $m_{g_A} > 21$ GeV.

X^0 (Heavy Boson) Searches in Z Decays

Searches for radiative transition of Z to a lighter spin-0 state X^0 decaying to hadrons, a lepton pair, a photon pair, or invisible particles as shown in the comments. The limits are for the product of branching ratios.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[227] ACCIARRI	97Q	L3	$X^0 \rightarrow$ invisible particle(s)
		[228] ACTON	93E	OPAL	$X^0 \rightarrow \gamma\gamma$
		[229] ABREU	92D	DLPH	$X^0 \rightarrow$ hadrons
		[230] ADRIANI	92F	L3	$X^0 \rightarrow$ hadrons
		[231] ACTON	91	OPAL	$X^0 \rightarrow$ anything
$<1.1 \times 10^{-4}$	95	[232] ACTON	91B	OPAL	$X^0 \rightarrow e^+e^-$
$<9\ \times 10^{-5}$	95	[232] ACTON	91B	OPAL	$X^0 \rightarrow \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[232] ACTON	91B	OPAL	$X^0 \rightarrow \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[233] ADEVA	91D	L3	$X^0 \rightarrow e^+e^-$
$<2.3 \times 10^{-4}$	95	[233] ADEVA	91D	L3	$X^0 \rightarrow \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[234] ADEVA	91D	L3	$X^0 \rightarrow$ hadrons
$<8\ \times 10^{-4}$	95	[235] AKRAWY	90J	OPAL	$X^0 \rightarrow$ hadrons

[227] See Fig. 4 of ACCIARRI 97Q for the upper limit on $B(Z \rightarrow \gamma X^0;\ E_\gamma > E_{\text{min}})$ as a function of E_{min}.

[228] ACTON 93E give $\sigma(e^+e^- \rightarrow X^0\gamma)\cdot B(X^0 \rightarrow \gamma\gamma) < 0.4$ pb (95%CL) for $m_{X^0}=60 \pm 2.5$ GeV. If the process occurs via s-channel γ exchange, the limit translates to $\Gamma(X^0)\cdot B(X^0 \rightarrow \gamma\gamma)^2 < 20$ MeV for $m_{X^0} = 60 \pm 1$ GeV.

[229] ABREU 92D give $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) <(3\text{–}10)$ pb for $m_{X^0} =$ 10–78 GeV. A very similar limit is obtained for spin-1 X^0.

[230] ADRIANI 92F search for isolated γ in hadronic Z decays. The limit $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) <(2\text{–}10)$ pb (95%CL) is given for $m_{X^0} =$ 25–85 GeV.

[231] ACTON 91 searches for $Z \rightarrow Z^* X^0$, $Z^* \rightarrow e^+e^-$, $\mu^+\mu^-$, or $\nu\bar{\nu}$. Excludes any new scalar X^0 with $m_{X^0} < 9.5$ GeV/c if it has the same coupling to ZZ^* as the MSM Higgs boson.

[232] ACTON 91B limits are for $m_{X^0} =$ 60–85 GeV.

[233] ADEVA 91D limits are for $m_{X^0} =$ 30–89 GeV.

[234] ADEVA 91D limits are for $m_{X^0} =$ 30–86 GeV.

[235] AKRAWY 90J give $\Gamma(Z \rightarrow \gamma X^0)\cdot B(X^0 \rightarrow \text{hadrons}) < 1.9$ MeV (95%CL) for m_{X^0} = 32–80 GeV. We divide by $\Gamma(Z) = 2.5$ GeV to get product of branching ratios. For nonresonant transitions, the limit is $B(Z \rightarrow \gamma q\bar{q}) < 8.2$ MeV assuming three-body phase space distribution.

MASS LIMITS for a Heavy Neutral Boson Coupling to e^+e^-

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 55–61		[236] ODAKA	89	VNS	$\Gamma(X^0 \rightarrow e^+e^-) \cdot B(X^0 \rightarrow \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[237] DERRICK	86	HRS	$\Gamma(X^0 \rightarrow e^+e^-)=6$ MeV
>46.6	95	[238] ADEVA	85	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)=10$ keV
>48	95	[238] ADEVA	85	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)=4$ MeV
		[239] BERGER	85B	PLUT	
none 39.8–45.5		[240] ADEVA	84	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)=10$ keV
>47.8	95	[240] ADEVA	84	MRKJ	$\Gamma(X^0 \rightarrow e^+e^-)=4$ MeV
none 39.8–45.2		[240] BEHREND	84C	CELL	
>47	95	[240] BEHREND	84C	CELL	$\Gamma(X^0 \rightarrow e^+e^-)=4$ MeV

[236] ODAKA 89 looked for a narrow or wide scalar resonance in $e^+e^- \rightarrow$ hadrons at E_{cm} = 55.0–60.8 GeV.

[237] DERRICK 86 found no deviation from the Standard Model Bhabha scattering at $E_{\text{cm}}=$ 29 GeV and set limits on the possible scalar boson e^+e^- coupling. See their figure 4 for excluded region in the $\Gamma(X^0 \rightarrow e^+e^-)$-$m_{X^0}$ plane. Electronic chiral invariance requires a parity doublet of X^0, in which case the limit applies for $\Gamma(X^0 \rightarrow e^+e^-) =$ 3 MeV.

[238] ADEVA 85 first limit is from 2γ, $\mu^+\mu^-$, hadrons assuming X^0 is a scalar. Second limit is from e^+e^- channel. E_{cm} = 40–47 GeV. Supersedes ADEVA 84.

[239] BERGER 85B looked for effect of spin-0 boson exchange in $e^+e^- \rightarrow e^+e^-$ and $\mu^+\mu^-$ at $E_{\text{cm}} = 34.7$ GeV. See Fig. 5 for excluded region in the $m_{X^0} - \Gamma(X^0)$ plane.

[240] ADEVA 84 and BEHREND 84C have E_{cm} = 39.8–45.5 GeV. MARK-J searched X^0 in $e^+e^- \rightarrow$ hadrons, 2γ, $\mu^+\mu^-$, e^+e^- and CELLO in the same channels plus τ pair. No narrow or broad X^0 is found in the energy range. They also searched for the effect of X^0 with $m_X > E_{\text{cm}}$. The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for $\Gamma(X^0 \rightarrow e^+e^-) = 2$ MeV if X^0 is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.

Search for X^0 Resonance in e^+e^- Collisions

The limit is for $\Gamma(X^0 \rightarrow e^+e^-) \cdot B(X^0 \rightarrow f)$, where f is the specified final state. Spin 0 is assumed for X^0.

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<10^3$	95	[241] ABE	93C	VNS	$\Gamma(ee)$
<(0.4–10)	95	[242] ABE	93C	VNS	$f = \gamma\gamma$
<(0.3–5)	95	[243,244] ABE	93D	TOPZ	$f = \gamma\gamma$
<(2–12)	95	[243,244] ABE	93D	TOPZ	f = hadrons
<(4–200)	95	[244,245] ABE	93D	TOPZ	$f = ee$
<(0.1–6)	95	[244,245] ABE	93D	TOPZ	$f = \mu\mu$
<(0.5–8)	90	[246] STERNER	93	AMY	$f = \gamma\gamma$

[241] Limit is for $\Gamma(X^0 \rightarrow e^+e^-)$ m_{X^0} = 56–63.5 GeV for $\Gamma(X^0) = 0.5$ GeV.

[242] Limit is for m_{X^0} = 56–61.5 GeV and is valid for $\Gamma(X^0) \ll 100$ MeV. See their Fig. 5 for limits for $\Gamma = 1{,}2$ GeV.

[243] Limit is for m_{X^0} = 57.2–60 GeV.

[244] Limit is valid for $\Gamma(X^0) \ll 100$ MeV. See paper for limits for $\Gamma = 1$ GeV and those for $J = 2$ resonances.

[245] Limit is for m_{X^0} = 56.6–60 GeV.

[246] STERNER 93 limit is for m_{X^0} = 57–59.6 GeV and is valid for $\Gamma(X^0) < 100$ MeV. See their Fig. 2 for limits for $\Gamma = 1{,}3$ GeV.

Search for X^0 Resonance in Two-Photon Process

The limit is for $\Gamma(X^0) \cdot B(X^0 \rightarrow \gamma\gamma)^2$. Spin 0 is assumed for X^0.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	95	[247] ACTON	93E	OPAL	$m_{X^0}=60 \pm 1$ GeV
<2.9	95	BUSKULIC	93F	ALEP	$m_{X^0} \sim 60$ GeV

[247] ACTON 93E limit for a $J = 2$ resonance is 0.8 MeV.

Search for X^0 Resonance in $e^+e^- \rightarrow X^0\gamma$

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[248] ADAM	96C	DLPH	X^0 decaying invisibly

[248] ADAM 96C is from the single photon production cross at $\sqrt{s}$=130, 136 GeV. The upper bound is less than 3 pb for X^0 masses between 60 and 130 GeV. See their Fig. 5 for the exact bound on the cross section $\sigma(e^+e^- \rightarrow \gamma X^0)$.

Search for X^0 Resonance in $Z \rightarrow f\bar{f}X^0$

The limit is for $B(Z \rightarrow f\bar{f}X^0) \cdot B(X^0 \rightarrow F)$ where f is a fermion and F is the specified final state. Spin 0 is assumed for X^0.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[249] ABREU	96T	DLPH	f=e,μ,τ; F=$\gamma\gamma$
$<3.7 \times 10^{-6}$	95	[250] ABREU	96T	DLPH	f=ν; F=$\gamma\gamma$
		[251] ABREU	96T	DLPH	f=q; F=$\gamma\gamma$
$<6.8 \times 10^{-6}$	95	[250] ACTON	93E	OPAL	f=e,μ,τ; F=$\gamma\gamma$
$<5.5 \times 10^{-6}$	95	[250] ACTON	93E	OPAL	f=q; F=$\gamma\gamma$
$<3.1 \times 10^{-6}$	95	[250] ACTON	93E	OPAL	f=ν; F=$\gamma\gamma$
$<6.5 \times 10^{-6}$	95	[250] ACTON	93E	OPAL	f=e,μ; F=$\ell\bar{\ell}$, $q\bar{q}$, $\nu\bar{\nu}$
$<7.1 \times 10^{-6}$	95	[250] BUSKULIC	93F	ALEP	f=e,μ; F=$\ell\bar{\ell}$, $q\bar{q}$, $\nu\bar{\nu}$
		[252] ADRIANI	92F	L3	f=q; F=$\gamma\gamma$

[249] ABREU 96T obtain limit as a function of m_{X^0}. See their Fig. 6.

[250] Limit is for m_{X^0} around 60 GeV.

[251] ABREU 96T obtain limit as a function of m_{X^0}. See their Fig. 15.

[252] ADRIANI 92F give $\sigma_Z \cdot B(Z \rightarrow q\bar{q}X^0) \cdot B(X^0 \rightarrow \gamma\gamma) < (0.75\text{–}1.5)$ pb (95%CL) for m_{X^0} = 10–70 GeV. The limit is 1 pb at 60 GeV.

Search for X^0 Resonance in $p\bar{p} \rightarrow WX^0$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[253] ABE	97W	CDF	$X^0 \rightarrow b\bar{b}$

[253] ABE 97W search for X^0 production associated with W in $p\bar{p}$ collisions at E_{cm}=1.8 TeV. The 95%CL upper limit on the production cross section times the branching ratio for $X^0 \rightarrow b\bar{b}$ ranges from 14 to 19 pb for X^0 mass between 70 and 120 GeV. See their Fig. 3 for upper limits of the production cross section as a funciton of m_{X^0}.

Search for Resonance X, Y in $e^+ e^- \rightarrow X Y$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[254] ALEXANDER	97B	OPAL	$X \rightarrow 2$ jets, $Y \rightarrow 2$ jets
	[255] BUSKULIC,D	96	ALEP	$X \rightarrow 2$ jets, $Y \rightarrow 2$ jets

[254] ALEXANDER 97B search for the associated production of two massive particles decaying into quarks in $e^+ e^-$ collisions at $\sqrt{s}$=130–136 GeV. The 95%CL upper limits on $\sigma(e^+ e^- \rightarrow X Y)$ range from 2.7 to 4.5 pb for $95 < m_X + m_Y < 120$ GeV.

[255] BUSKULIC,D 96 observed an excess of four-jet production cross section in $e^+ e^-$ collisions at $\sqrt{s}$=130–136 GeV and find an enhancement in the sum of two dijet masses around 105 GeV.

Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-5}$	90	[256] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0 \gamma$, $m_{X^0} < 5$ GeV
$< 3 \times 10^{-5}$–6×10^{-3}	90	[257] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0 \overline{X}^0 \gamma$, $m_{X^0} < 3.9$ GeV
$<5.6 \times 10^{-5}$	90	[258] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow X^0 \gamma$, $m_{X^0} < 7.2$ GeV
		[259] ALBRECHT	89	ARG	

[256] BALEST 95 two-body limit is for pseudoscalar X^0. The limit becomes $< 10^{-4}$ for $m_{X^0} < 7.7$ GeV.

[257] BALEST 95 three-body limit is for phase-space photon energy distribution and angular distribution same as for $\Upsilon \rightarrow g g \gamma$.

[258] ANTREASYAN 90C assume that X^0 does not decay in the detector.

[259] ALBRECHT 89 give limits for $B(\Upsilon(1S), \Upsilon(2S) \rightarrow X^0 \gamma) \cdot B(X^0 \rightarrow \pi^+ \pi^-, K^+ K^-, p\overline{p})$ for $m_{X^0} < 3.5$ GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABBOTT 98E PRL 80 2051 B. Abbott+ (D0 Collab.)
ABBOTT 97B PRL 79 4321 +Abolins, Acharya+ (D0 Collab.)
ABE 97F PRL 78 2906 +Akimoto, Akopian, Albrow, Amendolia+ (CDF Collab.)
ABE 97G PR D55 R5263 +Akimoto, Akopian, Albrow, Amendolia+ (CDF Collab.)
ABE 97S PRL 79 2192 +Akimoto, Akopian, Albrow, Amendolia+ (CDF Collab.)
ABE 97W PRL 79 3819 F. Abe+ (CDF Collab.)
ABE 97X PRL 79 4327 +Akimoto, Akopian, Albrow, Amadon+ (CDF Collab.)
ACCIARRI 97Q PL B412 201 M. Acciarri+ (L3 Collab.)
ALEXANDER 97B ZPHY C73 201 G. Alexander+ (OPAL Collab.)
ARIMA 97 PR D55 19 +Odaka, Ogawa, Shirai, Tsuboyama+ (VENUS Collab.)
BARATE 97B PL B399 329 +Buskulic, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
BARENBOIM 97 PR D55 4213 +Bernabeu, Prades, Raidal (VALE, IFIC)
DEANDREA 97 PL B409 277 (MARS)
DERRICK 97 ZPHY C73 613 M. Derrick+ (ZEUS Collab.)
GROSSMAN 97 PR D55 2768 +Ligeti, Nardi (REHO, CIT)
JADACH 97 PL B408 281 +Ward, Was (CERN, INPK, TENN, SLAC)
STAHL 97 ZPHY C74 73 A. Stahl, H. Voss (BONN)
ABACHI 96C PRL 76 3271 +Abbott, Abolins, Acharya, Adam+ (D0 Collab.)
ABACHI 96D PL B385 471 +Abbott, Abolins, Acharya, Adam+ (D0 Collab.)
ABREU 96T ZPHY C72 179 +Adam, Adye, Agasi, Ajinenko, Aleksan+ (DELPHI Collab.)
ADAM 96C PL B380 471 +Adye, Agasi, Ajinenko, Aleksan+ (DELPHI Collab.)
AID 96B PL B369 173 +Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
ALLET 96 PL B383 139 +Bodek, Camps, Deutsch+ (VILL, LEUV, LOUV, WISC)
BUSKULIC 96N PL B378 373 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
BUSKULIC,D 96 ZPHY C71 179 D. Buskulic+ (ALEPH Collab.)
ABACHI 95E PL B358 405 +Abbott, Abolins, Acharya, Adam, Adams+ (D0 Collab.)
ABACHI 95G PRL 75 3618 +Abbott, Abolins, Acharya, Adam, Adams+ (D0 Collab.)
ABE 95 PR D51 R949 +Albrow, Amidei, Antos, Anway-Wiese+ (CDF Collab.)
ABE 95M PRL 74 2900 +Albrow, Amidei, Antos, Anway-Wiese+ (CDF Collab.)
ABE 95N PRL 74 3538 +Albrow, Amendolia, Amidei, Antos+ (CDF Collab.)
ABE 95U PRL 75 1012 +Albrow, Amendolia, Amidei, Antos+ (CDF Collab.)
ABREU 95M ZPHY C65 603 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AID 95 PL B353 578 +Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
BALEST 95 PR D51 2053 +Cho, Ford, Johnson+ (CLEO Collab.)
KUZNETSOV 95 PRL 75 794 +Serebrov, Stepanenko+ (PNPI, KIAE, HARV, NIST)
KUZNETSOV 95B PAN 58 2113 +Mikheev (YARO)
Translated from YAF 58 2228.
MIZUKOSHI 95 NP B443 20 +Eboli, Gonzalez-Garcia (SPAUL, CERN)
NARDI 95 PL B344 225 +Roulet, Tommasini (MICH, CERN)
ABACHI 94B PRL 72 965 +Abbott, Abolins, Acharya, Adam+ (D0 Collab.)
ABREU 94O ZPHY C64 183 +Adam, Adye, Agasi, Ajinenko, Aleksan+ (DELPHI Collab.)
AHMED 94B ZPHY C64 545 +Aid, Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
BHATTACH... 94 PL B336 100 Bhattacharyya, Ellis, Sridhar (CERN)
Also 94B PL B338 522 (erratum) Bhattacharyya, Ellis, Sridhar (CERN)
BHATTACH... 94B PL B338 522 (erratum) Bhattacharyya, Ellis, Sridhar (CERN)
BUSKULIC 94 ZPHY C62 539 +Casper, De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
DAVIDSON 94 ZPHY C61 613 +Bailey, Campbell (CFPA, TNTO, ALBE)
KUZNETSOV 94 PL B329 295 +Mikheev (YARO)
KUZNETSOV 94B JETPL 60 315 +Serebrov, Stepanenko+ (PNPI, KIAE, HARV, NIST)
Translated from ZETFP 60 311.
LEURER 94 PR D50 536 (REHO)
LEURER 94B PR D49 333 (REHO)
Also 93 PRL 71 1324 Leurer (REHO)
MAHANTA 94 PL B337 128 (MEHTA)
SEVERIJNS 94 PRL 73 611 (erratum) + (LOUV, WISC, LEUV, ETH, MASA)
VILAIN 94B PL B332 465 +Wilquet, Beyer, Flegel, Grote+ (CHARM II Collab.)
ABE 93C PL B302 119 +Amako, Arai, Arima, Asano, Chiba+ (VENUS Collab.)
ABE 93D PL B304 373 +Adachi, Awa, Aoki, Belusevic, Emi+ (TOPAZ Collab.)
ABE 93G PRL 71 2542 +Albrow, Akimoto, Amidei, Anway-Wiese+ (CDF Collab.)
ABE 93I PR D48 R3939 +Albrow, Amidei, Anway-Wiese, Apollinari+ (CDF Collab.)
ABREU 93J PL B316 620 +Adam, Adye, Agasi, Aleksan, Alekseev+ (DELPHI Collab.)
ABT 93 NP B396 3 +Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
ACTON 93E PL B311 391 +Akers, Alexander+ (OPAL Collab.)
ADRIANI 93D PL B306 187 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ADRIANI 93M PRPL 236 1 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ALITTI 93 NP B400 3 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
ALLEN 93 PR D47 11 +Chen, Doe, Hausammann+ (UCI, LANL, ANL, UMD)
ALTARELLI 93B PL B318 139 +Casalbuoni+ (CERN, FIRZ, GEVA, PADO)
BHATTACH... 93 PR D47 R3693 Bhattacharyya+ (CALC, JADA, ICTP, AHMED, BOSE)
BUSKULIC 93F PL B308 425 +De Bonis, Decamp, Chez, Goy, Lees+ (ALEPH Collab.)
DERRICK 93 PL B306 173 +Krakauer, Magill, Musgrave, Repond+ (ZEUS Collab.)
RIZZO 93 PR D48 4470 (ANL)
SEVERIJNS 93 PRL 70 4047 +Gimeno-Nogues+ (LOUV, WISC, LEUV, ETH, MASA)
Also 94 PRL 73 611 (erratum) Severijns+ (LOUV, WISC, LEUV, ETH, MASA)
STERNER 93 PL B303 385 +Abashian, Gotow, Haim, Mattson, Morgan+(AMY Collab.)
ABE 92B PRL 68 1463 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABREU 92D ZPHY C53 555 +Adam, Adami, Adye, Akesson, Alekseev+(DELPHI Collab.)
ABREU 92F PL B275 222 +Adam, Adami, Adye, Akesson, Alekseev+(DELPHI Collab.)
ADRIANI 92F PL B292 472 +Aguilar-Benitez, Ahlen, Akbari, Alcarez+ (L3 Collab.)
ALITTI 92E PL B274 507 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
DECAMP 92 PRPL 216 253 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DELAGUILA 92 NP B372 3 del Aguila+ (CERN, GRAN, MPIM, BRUXT, MADE)
Also 91C NP B361 45 del Aguila, Moreno, Quiros (BARC, MADE)
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
LANGACKER 92B PR D45 278 +Luo (PENN)
LAYSSAC 92 ZPHY C53 97 +Renard, Verzegnassi (MONP, LAPP)
LAYSSAC 92B PL B287 267 +Renard, Verzegnassi (MONP, TRSTT)
LEIKE 92 PL B291 187 +Riemann, Riemann (BERL, CERN)
LEP 92 PL B276 247 +ALEPH, DELPHI, L3, OPAL (LEP Collabs.)
MISHRA 92 PRL 68 3499 +Leung, Arroyo+ (COLU, CHIC, FNAL, ROCH, WISC)
POLAK 92 PL B276 492 +Zralek (SILES)
POLAK 92B PR D46 3871 +Zralek (SILES)
RENTON 92 ZPHY C56 355 (OXF)
ABE 91D PRL 67 2418 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 91F PRL 67 2609 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ACTON 91 PL B268 122 +Alexander, Allison, Allport+ (OPAL Collab.)
ACTON 91B PL B273 338 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADEVA 91B PL B261 169 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 91D PL B262 155 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALEXANDER 91 PL B263 123 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ALITTI 91 ZPHY C49 17 +Ansari, Ansorge, Autiero, Bareyre+ (UA2 Collab.)
ALTARELLI 91 PL B261 146 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
ALTARELLI 91B PL B263 459 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
Also 90 PL B245 669 Altarelli, Casalbuoni, Feruglio, Gatto(CERN, LECE, GEVA)
AQUINO 91 PL B261 280 +Fernandez, Garcia (CINV, PUEB)
BUCHMUEL... 91 PL B267 395 Buchmueller, Greub, Minkowski (DESY, BERN)
COLANGELO 91 PL B253 154 +Nardulli (BARI)
CUYPERS 91 PL B259 173 +Falk, Frampton (DURH, HARV, UNCCH)
DELAGUILA 91 PL B254 497 del Aguila, Moreno, Quiros (BARC, MADE, CERN)
FARAGGI 91 MPL A6 61 +Nanopoulos (TAMU)
GEIREGAT 91 PL B259 499 +Vilain, Wilquet, Binder, Burkard+ (CHARM II Collab.)
GONZALEZ-G... 91 PL B259 365 Gonzalez-Garcia, Valle (VALE)
Also 90C NP B345 312 Gonzalez-Garcia, Valle (VALE)
MAHANTHAP... 91 PR D43 3093 Mahanthappa, Mohapatra (COLO)
Also 91B PR D44 1616 erratum Mahanthappa, Mohapatra (COLO)
POLAK 91 NP B363 385 +Zralek (SILES)
RIZZO 91 PR D44 202 (WISC, ISU)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
ABE 90F PL B246 297 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABE 90G PRL 65 2243 +Amidei, Apollinari, Atac+ (CDF Collab.)
ABE 90H PR D41 1722 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALLEN 90 PRL 64 1330 +Chen, Doe+ (UCI, LASL, UMD)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
BARGER 90B PR D42 152 +Hewett, Rizzo (WISC, ISU)
GLASHOW 90 PR D42 3224 +Sarid (HARV)
GLASHOW 90B PRL 64 725 +Sarid (HARV)
GONZALEZ-G... 90D PL B240 163 Gonzalez-Garcia, Valle (VALE)
GRIFOLS 90 NP B331 244 +Masso (BARC)
GRIFOLS 90C MPL A5 2657 (BARC)
GRIFOLS 90D PR D42 3293 +Masso, Rizzo (BARC, CERN, WISC, ISU)
HAGIWARA 90 PR D41 815 +Najima, Sakuda, Terunuma (KEK, DURH, YCC, HIRO)
HE 90B PL B240 441 +Joshi, Volkas (MELB)
Also 90C PL B244 580 erratum He, Joshi, Volkas (MELB)
KIM 90 PL B240 243 +Breedon, Ko, Lander, Maeshima, Malchow+(AMY Collab.)
LOPEZ 90 PL B241 392 +Nanopoulos (TAMU)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
BARBIERI 89B PR D39 1229 +Mohapatra (PISA, UMD)
DELAGUILA 89 PR D40 2481 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90B PR D41 134 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90C PR D42 262 erratum del Aguila, Moreno, Quiros (BARC, MADE)
DORENBOS... 89 ZPHY C41 567 Dorenbosch, Udo, Allaby, Amaldi+ (CHARM Collab.)
GEIREGAT 89 PL B232 539 +Vilain, Wilquet, Bergsma, Binder+ (CHARM II Collab.)
LANGACKER 89B PR D40 1569 +Uma Sankar (PENN)
ODAKA 89 JPSJ 58 3037 +Kondo, Abe, Amako+ (VENUS Collab.)
ROBINETT 89 PR D39 834 (PSU)
ALBAJAR 88B PL B209 127 +Albrow, Allkofer, Astbury, Aubert+ (UA1 Collab.)
BAGGER 88 PR D37 1188 +Schmidt, King (HARV, BOST)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BERGSTROM 88 PL B212 386 (STOH)
COSTA 88 NP B297 244 +Ellis, Fogli+ (PADO, CERN, BARI, WISC, LBL)
CUYPERS 88 PRL 60 1237 +Frampton (UNCCH)
DONCHESKI 88 PL B206 137 +Grotch, Robinett (PSU)
DONCHESKI 88B PR D38 412 +Grotch, Robinett (PSU)
ELLIS 88 PL B202 417 Ellis, Franzini, Zwirner (CERN, UCB, LBL)
RAFFELT 88 PRL 60 1793 +Seckel (UCB, LLL, UCSC)
AMALDI 87 PR D36 1385 +Bohm, Durkin, Langacker+ (CERN, AACH3, OSU+)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
BARTEL 87B ZPHY C36 15 +Becker, Felst+ (JADE Collab.)
MARCIANO 87 PR D35 1672 +Sirlin (BNL, NYU)
ARNISON 86B EPL 1 327 +Albrow, Allkofer+ (UA1 Collab.)
BARGER 86B PRL 56 30 +Deshpande, Whisnant (WISC, OREG, FSU)
BEHREND 86B PL B178 452 +Buerger, Criegee, Fenner, Field+ (CELLO Collab.)
DERRICK 86 PL 166B 463 +Gan, Kooijman, Loos+ (HRS Collab.)
Also 86B PR D34 3286 Derrick, Gan, Kooijman, Loos, Musgrave+ (HRS Collab.)
DURKIN 86 PL 166B 436 +Langacker (PENN)
ELLIS 86 PL 167B 457 +Enqvist, Nanopoulos, Sarkar (CERN, OXFTP)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
MOHAPATRA 86 PR D34 909 (UMD)
STEIGMAN 86 PL B176 33 +Olive, Schramm, Turner (BART, MINN+)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
ADEVA 85B PRL 55 665 +Becker, Becker-Szendy+ (Mark-J Collab.)
BERGER 85B ZPHY C27 341 +Deuter, Genzel, Lackas, Pielorz+ (PLUTO Collab.)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
ADEVA 84 PRL 53 134 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BEHREND 84C PL 140B 130 +Burger, Criegee, Fenner+ (CELLO Collab.)
ARNISON 83D PL 129B 273 +Astbury, Aubert, Bacci+ (UA1 Collab.)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
DESHPANDE 83 PR D27 1193 +Johnson (OREG)
BEALL 82 PRL 48 848 +Bander, Soni (UCI, UCLA)
SHANKER 82 NP B204 375 (TRIU)
DIMOPOUL... 81 NP B182 77 Dimopoulos, Raby, Kane (STAN, MICH)
RIZZO 81 PR D24 704 +Senjanovic (BNL)
STEIGMAN 79 PRL 43 239 +Olive, Schramm (BART, EFI)

Axions (A^0) and Other Very Light Bosons, Searches for

AXIONS AND OTHER VERY LIGHT BOSONS

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This review is divided into three parts:

Part I (Theory)
Part II (Astrophysical Constraints)
Part III (Experimental Limits)

AXIONS AND OTHER VERY LIGHT BOSONS, PART I (THEORY)

(by H. Murayama)

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. They arise if there is a global continuous symmetry in the theory that is spontaneously broken in the vacuum. If the symmetry is exact, it results in a massless Nambu–Goldstone (NG) boson. If there is a small explicit breaking of the symmetry, either already in the Lagrangian or due to quantum mechanical effects such as anomalies, the would-be NG boson acquires a finite mass; then it is called a pseudo-NG boson. Typical examples are axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries. This Review provides brief descriptions of each of them and their motivations.

One common characteristic for all these particles is that their coupling to the Standard Model particles are suppressed by the energy scale of symmetry breaking, *i.e.* the decay constant f, where the interaction is described by the Lagrangian

$$\mathcal{L} = \frac{1}{f}(\partial_\mu \phi) J^\mu , \tag{1}$$

where J^μ is the Noether current of the spontaneously broken global symmetry.

An axion gives a natural solution to the strong CP problem: why the effective θ-parameter in the QCD Lagrangian $\mathcal{L}_\theta = \theta_{eff} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \widetilde{F}^a_{\mu\nu}$ is so small ($\theta_{eff} \lesssim 10^{-9}$) as required by the current limits on the neutron electric dipole moment, even though $\theta_{eff} \sim O(1)$ is perfectly allowed by the QCD gauge invariance. Here, θ_{eff} is the effective θ parameter after the diagonalization of the quark masses, and $F^{\mu\nu a}$ is the gluon field strength and $\widetilde{F}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma a}$. An axion is a pseudo-NG boson of a spontaneously broken Peccei–Quinn symmetry, which is an exact symmetry at the classical level, but is broken quantum mechanically due to the triangle anomaly with the gluons. The definition of the Peccei–Quinn symmetry is model dependent. As a result of the triangle anomaly, the axion acquires an effective coupling to gluons

$$\mathcal{L} = \left(\theta_{eff} - \frac{\phi_A}{f_A}\right) \frac{\alpha_s}{8\pi} F^{\mu\nu a} \widetilde{F}^a_{\mu\nu} , \tag{2}$$

where ϕ_A is the axion field. It is often convenient to *define* the axion decay constant f_A with this Lagrangian [6]. The QCD nonperturbative effect induces a potential for ϕ_A whose minimum is at $\phi_A = \theta_{eff} f_A$ cancelling θ_{eff} and solving the strong CP problem. The mass of the axion is inversely proportional to f_A as

$$m_A = 0.62 \times 10^{-3}\text{eV} \times (10^{10}\text{GeV}/f_A) . \tag{3}$$

The original axion model [1,5] assumes $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter ($\tan\beta$): the ratio of the vacuum expectation values of two Higgs fields. This model is excluded after extensive experimental searches for such an axion [7]. Observation of a narrow-peak structure in positron spectra from heavy ion collisions [8] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A \sim v$, but drop the constraints of tree-level flavor conservation, were proposed [9]. Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result [10].

The popular way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 coupling becomes weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [11,12]. Two classes of models are discussed commonly in the literature. One introduces new heavy quarks which carry Peccei–Quinn charge while the usual quarks and leptons do not (KSVZ axion or "hadronic axion") [11]. The other does not need additional quarks but requires two Higgs doublets, and all quarks and leptons carry Peccei–Quinn charges (DFSZ axion or "GUT-axion") [12]. All models contain at least one electroweak singlet scalar boson which acquires an expectation value and breaks Peccei–Quinn symmetry. The invisible axion with a large decay constant $f_A \sim 10^{12}$ GeV was found to be a good candidate of the cold dark matter component of the Universe [13](see Dark Matter review). The energy density is stored in the low-momentum modes of the axion field which are highly occupied and thus represent essentially classical field oscillations.

The constraints on the invisible axion from astrophysics are derived from interactions of the axion with either photons, electrons or nucleons. The strengths of the interactions are model dependent (*i.e.*, not a function of f_A only), and hence one needs to specify a model in order to place lower bounds on f_A. Such constraints will be discussed in Part II. Serious experimental searches for an invisible axion are underway; they typically rely on axion-photon coupling, and some of them assume that the axion is the dominant component of our galactic halo density. Part III will discuss experimental techniques and limits.

Familons arise when there is a global family symmetry broken spontaneously. A family symmetry interchanges generations or acts on different generations differently. Such a symmetry may explain the structure of quark and lepton masses and their mixings. A familon could be either a scalar or a pseudoscalar. For instance, an SU(3) family symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger family symmetries with separate groups of left-handed and right-handed fields, one also has pseudoscalar familons. Some of them have flavor-off-diagonal couplings such as $\partial_\mu \phi_F \bar{d}\gamma^\mu s/F_{ds}$ or $\partial_\mu \phi_F \bar{e}\gamma^\mu \mu/F_{\mu e}$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor-changing processes. For instance, $B(K^+ \to \pi^+ \phi_F) < 3 \times 10^{-10}$ [14] gives $F_{ds} > 3.4 \times 10^{11}$ GeV [15]. The constraints on familons primarily coupled to third generation are quite weak [15].

If there is a global lepton-number symmetry and if it breaks spontaneously, there is a Majoron. The triplet Majoron model [4] has a weak-triplet Higgs boson, and Majoron couples to Z. It is now excluded by the Z invisible-decay width. The model is viable if there is an additional singlet Higgs boson and if the Majoron is mainly a singlet [16]. In the singlet Majoron model [3], lepton-number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos which acquire Majorana masses. The left-handed neutrino masses are generated by a "seesaw" mechanism [17]. The scale of lepton number breaking can be much higher than the electroweak scale in this case. Astrophysical constraints require the decay constant to be $\gtrsim 10^9$ GeV [18].

There is revived interest in a long-lived neutrino, to improve Big-Bang Nucleosynthesis [19] or large scale structure formation theories [20]. Since a decay of neutrinos into electrons or photons is severely constrained, these scenarios require a familon (Majoron) mode $\nu_1 \to \nu_2 \phi_F$ (see, *e.g.*, Ref. 15 and references therein).

Other light bosons (scalar, pseudoscalar, or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see Ref. 21.

It has been widely argued that a fundamental theory will not possess global symmetries; gravity, for example, is expected to violate them. Global symmetries such as baryon number arise by accident, typically as a consequence of gauge symmetries. It has been noted [22] that the Peccei-Quinn symmetry, from this perspective, must also arise by accident and must hold to an extraordinary degree of accuracy in order to solve the strong CP problem. Possible resolutions to this problem, however, have been discussed [22,23]. String theory also provides sufficiently good symmetries, especially using a large compactification radius motivated by recent developments in M-theory [24].

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AXIONS AND OTHER VERY LIGHT BOSONS: PART II (ASTROPHYSICAL CONSTRAINTS)

(by G.G. Raffelt)

Low-mass weakly-interacting particles (neutrinos, gravitons, axions, baryonic or leptonic gauge bosons, *etc.*) are produced in hot plasmas and thus represent an energy-loss channel for stars. The strength of the interaction with photons, electrons, and nucleons can be constrained from the requirement that stellar-evolution time scales are not modified beyond observational limits. For detailed reviews see Refs. [1,2].

The energy-loss rates are steeply increasing functions of temperature T and density ρ. Because the new channel has to compete with the standard neutrino losses which tend to increase even faster, the best limits arise from low-mass stars, notably from horizontal-branch (HB) stars which have a helium-burning core of about 0.5 solar masses at $\langle\rho\rangle \approx 0.6 \times 10^4\,\mathrm{g\,cm^{-3}}$ and $\langle T\rangle \approx 0.7 \times 10^8\,\mathrm{K}$. The new energy-loss rate must not exceed about $10\,\mathrm{ergs\,g^{-1}\,s^{-1}}$ to avoid a conflict with the observed number ratio of HB stars in globular clusters. Likewise the ignition of helium in the degenerate cores of the preceding red-giant phase is delayed too much unless the same constraint holds at $\langle\rho\rangle \approx 2 \times 10^5\,\mathrm{g\,cm^{-3}}$ and $\langle T\rangle \approx 1 \times 10^8\,\mathrm{K}$. The white-dwarf luminosity function also yields useful bounds.

The new bosons X^0 interact with electrons and nucleons with a dimensionless strength g. For scalars it is a Yukawa coupling, for new gauge bosons (*e.g.*, from a baryonic or leptonic gauge symmetry) a gauge coupling. Axion-like pseudoscalars couple derivatively as $f^{-1}\bar\psi\gamma_\mu\gamma_5\psi\,\partial^\mu\phi_X$ with f an energy scale. Usually this is equivalent to $(2m/f)\bar\psi\gamma_5\psi\,\phi_X$ with m the mass of the fermion ψ so that $g = 2m/f$. For the coupling to electrons, globular-cluster stars yield the constraint

$$g_{Xe} \lesssim \begin{cases} 0.5 \times 10^{-12} & \text{for pseudoscalars [3] ,} \\ 1.3 \times 10^{-14} & \text{for scalars [4] ,} \end{cases} \tag{1}$$

if $m_X \lesssim 10\,\mathrm{keV}$. The Compton process $\gamma + {}^4\mathrm{He} \to {}^4\mathrm{He} + X^0$ limits the coupling to nucleons to $g_{XN} \lesssim 0.4 \times 10^{-10}$ [4].

Scalar and vector bosons mediate long-range forces which are severely constrained by "fifth-force" experiments [5]. In the massless case the best limits come from tests of the equivalence principle in the solar system, leading to

$$g_{B,L} \lesssim 10^{-23} \tag{2}$$

for a baryonic or leptonic gauge coupling [6].

In analogy to neutral pions, axions A^0 couple to photons as $g_{A\gamma}\mathbf{E}\cdot\mathbf{B}\,\phi_A$ which allows for the Primakoff conversion $\gamma \leftrightarrow A^0$ in external electromagnetic fields. The most restrictive limit arises from globular-cluster stars [2]

$$g_{A\gamma} \lesssim 0.6 \times 10^{-10}\,\mathrm{GeV}^{-1}\ . \tag{3}$$

The often-quoted "red-giant limit" [7] is slightly weaker.

The duration of the SN 1987A neutrino signal of a few seconds proves that the newborn neutron star cooled mostly by neutrinos rather than through an "invisible channel" such as right-handed (sterile) neutrinos or axions [8]. Therefore,

$$3 \times 10^{-10} \lesssim g_{AN} \lesssim 3 \times 10^{-7} \tag{4}$$

is excluded for the pseudoscalar Yukawa coupling to nucleons [2]. The "strong" coupling side is allowed because axions then escape only by diffusion, quenching their efficiency as an energy-loss channel [9]. Even then the range

$$10^{-6} \lesssim g_{AN} \lesssim 10^{-3} \tag{5}$$

is excluded to avoid excess counts in the water Cherenkov detectors which registered the SN 1987A neutrino signal [11].

In terms of the Peccei-Quinn scale f_A, the axion couplings to nucleons and photons are $g_{AN} = C_N m_N/f_A$ ($N = n$ or p) and $g_{A\gamma} = (\alpha/2\pi f_A)\,(E/N - 1.92)$ where C_N and E/N are model-dependent numerical parameters of order unity. With $m_A = 0.62\,\mathrm{eV}\,(10^7\,\mathrm{GeV}/f_A)$, Eq. (3) yields $m_A \lesssim 0.4\,\mathrm{eV}$ for $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limit is $m_A \lesssim 0.008\,\mathrm{eV}$ for KSVZ axions while it varies between about 0.004 and 0.012 eV for DFSZ axions, depending on the angle β which measures the ratio of two Higgs vacuum expectation values [10]. In view of the large uncertainties it is good enough to remember $m_A \lesssim 0.01\,\mathrm{eV}$ as a generic limit (Fig. 1).

In the early universe, axions come into thermal equilibrium only if $f_A \lesssim 10^8\,\mathrm{GeV}$ [12]. Some fraction of the relic axions end up in galaxies and galaxy clusters. Their decay $a \to 2\gamma$ contributes to the cosmic extragalactic background light and to line emissions from galactic dark-matter haloes and galaxy clusters. An unsuccessful "telescope search" for such features yields $m_a < 3.5\,\mathrm{eV}$ [13]. For $m_a \gtrsim 30\,\mathrm{eV}$, the axion lifetime is shorter than the age of the universe.

For $f_A \gtrsim 10^8\,\mathrm{GeV}$ cosmic axions are produced nonthermally. If inflation occurred after the Peccei-Quinn symmetry breaking or if $T_\mathrm{reheat} < f_A$, the "misalignment mechanism" [14] leads to a contribution to the cosmic critical density of

$$\Omega_A h^2 \approx 1.9 \times 3^{\pm1}\,(1\,\mu\mathrm{eV}/m_A)^{1.175}\,\Theta_\mathrm{i}^2 F(\Theta_\mathrm{i}) \tag{6}$$

where h is the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The stated range reflects recognized uncertainties of the cosmic conditions at the QCD phase transition and of the temperature-dependent axion mass. The function $F(\Theta)$ with $F(0) = 1$ and $F(\pi) = \infty$ accounts for anharmonic corrections to the axion

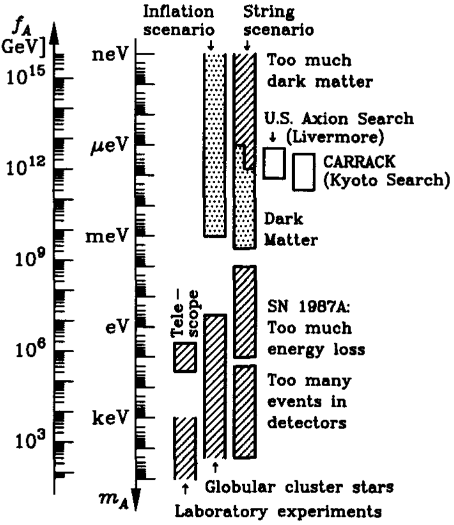

Figure 1: Astrophysical and cosmological exclusion regions (hatched) for the axion mass m_A or equivalently, the Peccei-Quinn scale f_A. An "open end" of an exclusion bar means that it represents a rough estimate; its exact location has not been established or it depends on detailed model assumptions. The globular cluster limit depends on the axion-photon coupling; it was assumed that $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limits depend on the axion-nucleon couplings; the shown case corresponds to the KSVZ model and approximately to the DFSZ model. The dotted "inclusion regions" indicate where axions could plausibly be the cosmic dark matter. Most of the allowed range in the inflation scenario requires fine-tuned initial conditions. In the string scenario the plausible dark-matter range is controversial as indicated by the step in the low-mass end of the "inclusion bar" (see main text for a discussion). Also shown is the projected sensitivity range of the search experiments for galactic dark-matter axions.

potential. Because the initial misalignment angle Θ_i can be very small or very close to π, there is no real prediction for the mass of dark-matter axions even though one would expect $\Theta_\mathrm{i}^2 F(\Theta_\mathrm{i}) \sim 1$ to avoid fine-tuning the initial conditions.

A possible fine-tuning of Θ_i is limited by inflation-induced quantum fluctuations which in turn lead to temperature fluctuations of the cosmic microwave background [15,16]. In a broad class of inflationary models one thus finds an upper limit to m_A where axions could be the dark matter. According to the most recent discussion [16] it is about 10^{-3} eV (Fig. 1).

If inflation did not occur at all or if it occurred before the Peccei-Quinn symmetry breaking with $T_\mathrm{reheat} > f_A$, cosmic axion strings form by the Kibble mechanism [17]. Their motion is damped primarily by axion emission rather than gravitational waves. After axions acquire a mass at the QCD phase transition they quickly become nonrelativistic and thus form a cold dark matter component. Battye and Shellard [18] found that the dominant source of axion radiation are string loops rather than long strings. At a cosmic time t the average loop creation size is parametrized as $\langle \ell \rangle = \alpha t$ while the radiation power is $P = \kappa\mu$ with μ the renormalized string tension. The loop contribution to the cosmic axion density is [18]

$$\Omega_A h^2 \approx 88 \times 3^{\pm 1} \left[(1+\alpha/\kappa)^{3/2} - 1\right] (1\,\mu\mathrm{eV}/m_A)^{1.175} \ , \quad (7)$$

where the stated nominal uncertainty has the same source as in Eq. (6). The values of α and κ are not known, but probably $0.1 < \alpha/\kappa < 1.0$ [18], taking the expression in square brackets to 0.15–1.83. If axions are the dark matter, we have

$$0.05 \lesssim \Omega_A h^2 \lesssim 0.50 \ , \quad (8)$$

where it was assumed that the universe is older than 10 Gyr, that the dark-matter density is dominated by axions with $\Omega_A \gtrsim 0.2$, and that $h \gtrsim 0.5$. This implies m_A = 6–2500 μeV for the plausible mass range of dark-matter axions (Fig. 1).

Contrary to Ref. 18, Sikivie *et al.* [19] find that the motion of global strings is strongly damped, leading to a flat axion spectrum. In Battye and Shellard's treatment the axion radiation is strongly peaked at wavelengths of order the loop size. In Sikivie *et al.*'s picture more of the string radiation goes into kinetic axion energy which is redshifted so that ultimately there are fewer axions. In this scenario the contributions from string decay and vacuum realignment are of the same order of magnitude; they are both given by Eq. (6) with Θ_i of order one. As a consequence, Sikivie *et al.* allow for a plausible range of dark-matter axions which reaches to smaller masses as indicated in Fig. 1.

The work of both groups implies that the low-mass end of the plausible mass interval in the string scenario overlaps with the projected sensitivity range of the U.S. search experiment for galactic dark-matter axions (Livermore) [20] and of the Kyoto search experiment CARRACK [21] as indicated in Fig. 1. (See also Part III of this Review by Hagmann, van Bibber, and Rosenberg.)

In summary, a variety of robust astrophysical arguments and laboratory experiments (Fig. 1) indicate that $m_A \lesssim 10^{-2}$ eV. The exact value of this limit may change with a more sophisticated treatment of supernova physics and/or the observation of the neutrino signal from a future galactic supernova, but a dramatic modification is not expected unless someone puts forth a completely new argument. The stellar-evolution limits shown in Fig. 1 depend on the axion couplings to various particles and thus can be irrelevant in fine-tuned models where, for example, the axion-photon coupling strictly vanishes. For nearly any m_A in the range generically allowed by stellar evolution, axions could be the cosmic dark matter, depending on the cosmological scenario realized in nature. It appears that our only practical chance to discover these "invisible" particles rests with the ongoing or future search experiments for galactic dark-matter.

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AXIONS AND OTHER VERY LIGHT BOSONS, PART III (EXPERIMENTAL LIMITS)

(by C. Hagmann, K. van Bibber, and L.J. Rosenberg)

In this section we review the experimental methodology and limits on light axions and light pseudoscalars in general. (A comprehensive overview of axion theory is given by H. Murayama in the Part I of this Review, whose notation we follow [1].) Within its scope are searches where the axion is assumed to be dark matter, searches where the Sun is presumed to be a source of axions, and purely laboratory experiments. We restrict the discussion to axions of mass $m_A < O(\text{eV})$, as the allowed range for the axion mass is nominally $10^{-6} < m_A < 10^{-2}$ eV. Experimental work in this range predominantly has been through the axion-photon coupling $g_{A\gamma}$, to which the present review is confined. As discussed in Part II of this Review by G. Raffelt, the lower bound derives from a cosmological overclosure argument, and the upper bound from SN1987A [2]. Limits from stellar evolution overlap seamlessly above that, connecting with accelerator-based limits which ruled out the original axion. There it was assumed that the Peccei-Quinn symmetry-breaking scale was the electroweak scale, *i.e.*, $f_A \sim 250$ GeV, implying axions of mass $m_A \sim O(100\,\text{keV})$. These earlier limits from nuclear transitions, particle decays, *etc.*, while not discussed here, are included in the Listings.

While the axion mass is well determined by the Peccei-Quinn scale, *i.e.*, $m_A = 0.62$ eV $(10^7\,\text{GeV}/f_A)$, the axion-photon coupling $g_{A\gamma}$ is not: $g_{A\gamma} = (\alpha/\pi f_A)\,g_\gamma$, with $g_\gamma = (E/N - 1.92)/2$, where E/N is a model-dependent number. It is noteworthy however, that two quite distinct models lead to axion-photon couplings which are not very different. For the case of axions imbedded in Grand Unified Theories, the DFSZ axion [3], $g_\gamma = 0.37$, whereas in one popular implementation of the "hadronic" class of axions, the KSVZ axion [4], $g_\gamma = -0.96$. The Lagrangian $L = g_{A\gamma}\,\mathbf{E}\cdot\mathbf{B}\,\phi_A$, with ϕ_A the axion field, permits the conversion of an axion into a single real photon in an external electromagnetic field, *i.e.*, a Primakoff interaction. In the case of relativistic axions, $k_\gamma - k_A \sim m_A^2/2\omega \ll \omega$, pertinent to several experiments below, coherent axion-photon mixing in long magnetic fields results in significant conversion probability even for very weakly coupled axions [5].

Below are discussed several experimental techniques constraining $g_{A\gamma}$, and their results. Also included are recent but yet-unpublished results, and projected sensitivities for experiments soon to be upgraded.

III.1. Microwave cavity experiments: Possibly the most promising avenue to the discovery of the axion presumes that axions constitute a significant fraction of the dark matter halo of our galaxy. The maximum likelihood density for the Cold Dark Matter (CDM) component of our galactic halo is $\rho_{\text{CDM}} = 7.5 \times 10^{-25}\text{g/cm}^3(450\,\text{MeV/cm}^3)$ [6]. That the CDM halo is in fact made of axions (rather than *e.g.* WIMPs) is in principle an independent assumption, however should very light axions exist they would almost necessarily be cosmologically abundant [2]. As shown by Sikivie [7], halo axions may be detected by their resonant conversion into a quasi-monochromatic microwave signal in a high-Q cavity permeated by a strong magnetic field. The cavity is tunable and the signal is maximum when the frequency $\nu = m_A(1 + O(10^{-6}))$, the width of the peak representing the virial distribution of thermalized axions in the galactic gravitational potential. The signal may possess ultra-fine structure due to axions recently fallen into the galaxy and not yet thermalized [8]. The feasibility of the technique was established in early experiments of small sensitive volume, $V = O(1\,\text{liter})$ [9,10] with High Electron Mobility Transistor (HEMT) amplifiers, which set limits on axions in the mass range $4.5 < m_A < 16.3\,\mu\text{eV}$, but at power sensitivity levels 2–3 orders of magnitude too high to see KSVZ and DFSZ axions (the conversion power $P_{A\to\gamma} \propto g^2_{A\gamma}$). A recent large-scale experiment ($B \sim 7.5\,\text{T}, V \sim 200\,\text{liter}$) has achieved sensitivity to KSVZ axions over a narrow mass range $2.77 < m_A < 3.3\,\mu\text{eV}$, and continues to take data [11]. The exclusion regions shown in Fig. 1 for Refs. [9–12] are all normalized to the best-fit Cold Dark Matter density $\rho_{\text{CDM}} = 7.5 \times 10^{-25}\text{g/cm}^3(450\,\text{MeV/cm}^3)$, and 90% CL. Recent developments in DC SQUID amplifiers [12] and Rydberg atom single-quantum detectors [13] promise dramatic improvements in noise temperature, which will enable rapid scanning of the axion mass range at or below the DFSZ limit. The region of the microwave cavity experiments is shown in detail in Fig. 2.

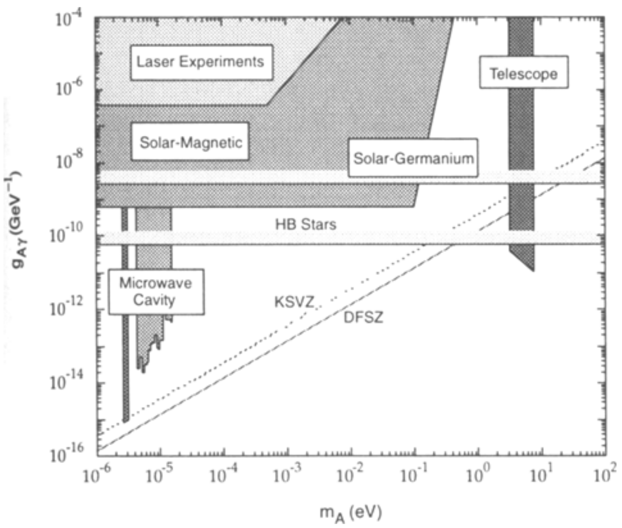

Figure 1: Exclusion region in mass vs. axion-photon coupling ($m_A, g_{A\gamma}$) for various experiments. The limit set by globular cluster Horizontal Branch Stars ("HB Stars") is shown for Ref. 2.

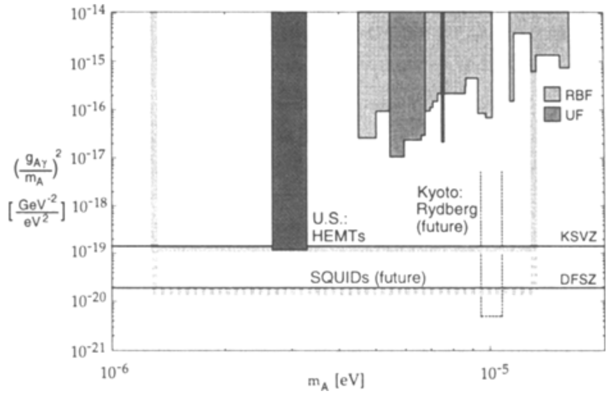

Figure 2: Exclusion region from the microwave cavity experiments, where the plot is flattened by presenting $(g_{A\gamma}/m_A)^2$ vs. m_A. The first-generation experiments (Rochester-BNL-FNAL, "RBF" [9]; University of Florida, "UF" [10]) and the US large-scale experiment in progress ("US" [11]) are all HEMT-based. Shown also is the full mass range to be covered by the latter experiment (shaded line), and the improved sensitivity when upgraded with DC SQUID amplifiers [12] (shaded dashed line). The expected performance of the Kyoto experiment based on a Rydberg atom single-quantum receiver (dotted line) is also shown [13].

III.2. Telescope search for eV axions: For axions of mass greater than about 10^{-1} eV, their cosmological abundance is no longer dominated by vacuum misalignment or string radiation mechanisms, but rather by thermal production. Their contribution to the critical density is small, $\Omega \sim 0.01\,(m_A/\text{eV})$. However, the spontaneous-decay lifetime of axions, $\tau(A \to 2\gamma) \sim 10^{25}\text{sec}(m_A/\text{eV})^{-5}$ while irrelevant for μeV axions, is short enough to afford a powerful constraint on such thermally produced axions in the eV range, by looking for a quasi-monochromatic photon line from galactic clusters. This line, corrected for Doppler shift, would be at half the axion mass and its width would be consistent with the observed virial motion, typically $\Delta\lambda/\lambda \sim 10^{-2}$. The expected line intensity would be of the order $I_A \sim 10^{-17}(m_A/3\,\text{eV})^7\text{erg}\,\text{cm}^{-2}\text{arcsec}^{-2}\text{Å}^{-1}\text{sec}^{-1}$ for DFSZ axions, comparable to the continuum night emission. The conservative assumption is made that the relative density of thermal axions fallen into the cluster gravitational potential reflects their overall cosmological abundance. A search for thermal axions in three rich Abell clusters was carried out at Kitt Peak National Laboratory [14]; no such line was observed between 3100–8300 Å (m_A = 3–8 eV) after "on-off field" subtraction of the atmospheric molecular background spectra. A limit everywhere stronger than $g_{A\gamma} < 10^{-10}\text{GeV}^{-1}$ is set, which is seen from Fig. 1 to easily exclude DFSZ axions throughout the mass range.

III.3. A search for solar axions: As with the telescope search for thermally produced axions above, the search for solar axions was stimulated by the possibility of there being a "1 eV window" for hadronic axions (*i.e.*, axions with no tree-level coupling to leptons), a "window" subsequently closed by an improved understanding of the evolution of globular cluster stars and SN1987A [2]. Hadronic axions would be copiously produced within our Sun's interior by a Primakoff process. Their flux at the Earth of $\sim 10^{12}\text{cm}^{-2}\text{sec}^{-1}(m_A/\text{eV})^2$, which is independent of the details of the solar model, is sufficient for a definitive test via the axion reconversion to photons in a large magnetic field. However, their average energy is $\sim$ 4 keV, implying an oscillation length in the vacuum of $2\pi(m_A^2/2\omega)^{-1} \sim O(\text{mm})$, precluding the mixing from achieving its theoretically maximum value in any practical magnet. It was recognized that one could endow the photon with an effective mass in a gas, $m_\gamma = \omega_{\text{pl}}$, thus permitting the axion and photon dispersion relationships to be matched [15]. A first simple implementation of this proposal was carried out using a conventional dipole magnet with a conversion volume of variable-pressure helium gas and a xenon proportional chamber as the x-ray detector [16]. The magnet was fixed in orientation to take data for $\sim$ 1000 sec/day. Axions were excluded for $g_{A\gamma} < 3.6 \times 10^{-9}\text{GeV}^{-1}$ for $m_A <$ 0.03 eV, and $g_{A\gamma} < 7.7 \times 10^{-9}\text{GeV}^{-1}$ for 0.03 eV< m_A <0.11 eV (95% CL). A more ambitious experiment has recently been commissioned, using a superconducting magnet on a telescope mount to track the Sun continuously. A preliminary exclusion limit of $g_{A\gamma} < 6 \times 10^{-10}\text{GeV}^{-1}$ (95% CL) has been set for $m_A <$ 0.03 eV [17].

Another search for solar axions has been carried out, using a single crystal germanium detector. It exploits the coherent conversion of axions into photons when their angle of incidence satisfies a Bragg condition with a crystalline plane. Analysis of 1.94 kg-yr of data from a 1 kg germanium detector yields a bound of $g_{A\gamma} < 2.7 \times 10^{-9}\text{GeV}^{-1}$ (95% CL), independent of mass up to $m_A \sim$ 1 keV [18].

III.4. Photon regeneration ("invisible light shining through walls"): Photons propagating through a transverse field (with **E**||**B**) may convert into axions. For light axions with $m_A^2 l/2\omega \ll 2\pi$, where l is the length of the magnetic field, the axion beam produced is colinear and coherent with the photon beam, and the conversion probability Π is given by $\Pi \sim (1/4)(g_{A\gamma}Bl)^2$. An ideal implementation for this limit is a laser beam propagating down a long, superconducting dipole magnet like those for high-energy physics accelerators. If another such dipole magnet is set up in line with the first, with an optical barrier interposed between them, then photons may be regenerated from the pure axion beam in the second magnet and detected [19]. The overall probability $P(\gamma \to A \to \gamma) = \Pi^2$. Such an experiment has been carried out, utilizing two magnets of length $l=$ 4.4 m and $B=$ 3.7 T. Axions with mass $m_A < 10^{-3}$ eV, and $g_{A\gamma} > 6.7 \times 10^{-7}\text{GeV}^{-1}$ were excluded at 95% CL [20,21]. With sufficient effort, limits comparable to those from stellar evolution would be achievable. Due to the $g_{A\gamma}^4$ rate suppression however, it does not seem feasible to reach standard axion couplings.

III.5. Polarization experiments: The existence of axions can affect the polarization of light propagating through a transverse magnetic field in two ways [22]. First, as the $E_\parallel$ component, but not the $E_\perp$ component will be depleted by the production of real axions, there will be in general a small rotation of the polarization vector of linearly polarized light. This effect will be a constant for all sufficiently light m_A such that the oscillation length is much longer than the magnet $(m_A^2 l/2\omega \ll 2\pi)$. For heavier axions, the effect oscillates and diminishes with increasing m_A, and vanishes for $m_A > \omega$. The second effect is birefringence of the vacuum, again because there can be a mixing of virtual axions in the $E_\parallel$ state, but not for the $E_\perp$ state. This will lead to light which is initially linearly polarized becoming elliptically polarized. Higher-order QED also induces vacuum birefringence, and is much stronger than the contribution due to axions. A search for both polarization-rotation and induced ellipticity has been carried out with the same magnets described in Sec. (III.4) above [21,23]. As in the case of photon regeneration, the observables are boosted linearly by the number of passes the laser beam makes in an optical cavity within the magnet. The polarization-rotation resulted in a stronger limit than that from ellipticity, $g_{A\gamma} <$ $3.6 \times 10^{-7}\text{GeV}^{-1}$ (95% CL) for $m_A < 5 \times 10^{-4}$ eV. The limits from ellipticity are better at higher masses, as they fall off smoothly and do not terminate at m_A. There are two experiments in construction with greatly improved sensitivity which while still far from being able to detect standard axions, should measure the QED "light-by-light" contribution for the first time [24,25]. The overall envelope for limits from the laser-based experiments in Sec. (III.4) and Sec. (III.5) is shown schematically in Fig. 1.

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A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
>0.2	BARROSO	82	ASTR	Standard Axion
>0.25	[1] RAFFELT	82	ASTR	Standard Axion
>0.2	[2] DICUS	78C	ASTR	Standard Axion
	MIKAELIAN	78	ASTR	Stellar emission
>0.3	[2] SATO	78	ASTR	Standard Axion
>0.2	VYSOTSKII	78	ASTR	Standard Axion

[1] Lower bound from 5.5 MeV γ-ray line from the sun.

[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

A^0 (Axion) and Other Light Boson (X^0) Searches in Stable Particle Decays

Limits are for branching ratios.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<3.0 \times 10^{-10}$	90		[3] ADLER	97	B787	$K^+ \to \pi^+ A^0$
$<5.0 \times 10^{-8}$	90		[4] KITCHING	97	B787	$K^+ \to \pi^+ A^0$ $(A^0 \to \gamma\gamma)$
$<5.2 \times 10^{-10}$	90		[5] ADLER	96	B787	$K^+ \to \pi^+ A^0$
$<2.8 \times 10^{-4}$	90		[6] AMSLER	96B	CBAR	$\pi^0 \to \gamma X^0$, $m_{X^0} < 65$ MeV
$<3 \times 10^{-4}$	90		[6] AMSLER	96B	CBAR	$\eta \to \gamma X^0$, $m_{X^0}=$ 50–200 MeV
$<4 \times 10^{-5}$	90		[6] AMSLER	96B	CBAR	$\eta' \to \gamma X^0$, $m_{X^0}=$ 50–925 MeV
$<6 \times 10^{-5}$	90		[6] AMSLER	94B	CBAR	$\pi^0 \to \gamma X^0$, m_{X^0}=65–125 MeV
$<6 \times 10^{-5}$	90		[6] AMSLER	94B	CBAR	$\eta \to \gamma X^0$, m_{X^0}=200–525 MeV
<0.007	90		[7] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=25 MeV
<0.002	90		[7] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=100 MeV
$<2 \times 10^{-7}$	90		[8] ATIYA	93B	B787	$K^+ \to \pi^+ A^0$
$<3 \times 10^{-13}$			[9] NG	93	COSM	$\pi^0 \to \gamma X^0$
$<1.1 \times 10^{-8}$	90		[10] ALLIEGRO	92	SPEC	$K^+ \to \pi^+ A^0$ $(A^0 \to e^+ e^-)$
$<5 \times 10^{-4}$	90		[11] ATIYA	92	B787	$\pi^0 \to \gamma X^0$
$<4 \times 10^{-6}$	90		[12] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$, $X^0 \to e^+ e^-$, m_{X^0}= 100 MeV
$<1 \times 10^{-7}$	90		[13] ATIYA	90B	B787	Sup. by KITCHING 97
$<1.3 \times 10^{-8}$	90		[14] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ $(A^0 \to e^+ e^-)$
$<1 \times 10^{-9}$	90	0	[15] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[16] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5–4) \times 10^{-6}$	90		[16] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV
		0	[17] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$
		0	[18] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$
			[19] ZHITNITSKII	79		Heavy axion

[3] ADLER 97 bound is for massless A^0.

[4] KITCHING 97 limit is for B($K^+ \to \pi^+ A^0$)·B($A^0 \to \gamma\gamma$) and applies for $m_{A^0} \simeq 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.

[5] ADLER 96 looked for a peak in missing-mass distribution. This work is an update of ATIYA 93. The limit is for massless stable A^0 particles and extends to m_{A^0}=80 MeV at the same level. See paper for dependence on finite lifetime.

[6] AMSLER 94B and AMSLER 96B looked for a peak in missing-mass distribution.

[7] The MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of X^0 decay modes. It applies to $\tau(X^0) > 10^{-23}$ sec.

[8] ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable A^0 of m_{A^0}=150–250 MeV, and the limit becomes stronger (10^{-8}) for m_{A^0}=180–240 MeV.

[9] NG 93 studied the production of X^0 via $\gamma\gamma \to \pi^0 \to \gamma X^0$ in the early universe at $T \simeq 1$ MeV. The bound on extra neutrinos from nucleosyntheis $\Delta N_\nu < 0.3$ (WALKER 91) is employed. It applies to $m_{X^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier X^0.

[10] ALLIEGRO 92 limit applies for m_{A^0}=150–340 MeV and is the branching ratio times the decay probability. Limit is $< 1.5 \times 10^{-8}$ at 99%CL.

[11] ATIYA 92 looked for a peak in missing mass distribution. The limit applies to m_{X^0}=0–130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires X^0 to be a vector particle.

[12] MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}$–10^{-11} sec. Limits between 2×10^{-4} and 4×10^{-6} are obtained for m_{X^0} = 25–120 MeV. Angular momentum conservation requires that X^0 has spin ≥ 1.

[13] ATIYA 90B limit is for B($K^+ \to \pi^+ A^0$)·B($A^0 \to \gamma\gamma$) and applies for $m_{A^0} = 50$ MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.

[14] KORENCHENKO 87 limit assumes $m_{A^0} = 1.7$ MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and B($A^0 \to e^+ e^-$) = 1..

[15] EICHLER 86 looked for $\pi^+ \to e^+ \nu A^0$ followed by $A^0 \to e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of A^0. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[16] YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+ X$. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.

[17] ASANO 82 at KEK set limits for B($K^+ \to \pi^+ A^0$) for m_{A^0} <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(A^0 \to n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s.

[18] ASANO 81B is KEK experiment. Set B($K^+ \to \pi^+ A^0$) $< 3.8 \times 10^{-8}$ at CL = 90%.

[19] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 (3 <m <40 MeV) contradicts experimental muon anomalous magnetic moments.

A^0 (Axion) Searches in Quarkonium Decays

Decay or transition of quarkonium. Limits are for branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.3 \times 10^{-5}$	90		[20] BALEST	95	CLEO	$\Upsilon(1S) \to A^0 \gamma$
$<4.0 \times 10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to A^0 \gamma$
			[21] ANTREASYAN	90C	RVUE	
$<5 \times 10^{-5}$	90		[22] DRUZHININ	87	ND	$\phi \to A^0 \gamma$ $(A^0 \to e^+ e^-)$
$<2 \times 10^{-3}$	90		[23] DRUZHININ	87	ND	$\phi \to A^0 \gamma$ $(A^0 \to \gamma\gamma)$
$<7 \times 10^{-6}$	90		[24] DRUZHININ	87	ND	$\phi \to A^0 \gamma$ ($A^0 \to$ missing)
$<3.1 \times 10^{-4}$	90	0	[25] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0 \gamma$ $(A^0 \to e^+ e^-)$

$<4 \times 10^{-4}$	90	0	[25] ALBRECHT 86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to \mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-)
$<8 \times 10^{-4}$	90	1	[26] ALBRECHT 86D	ARG	$\Upsilon(1S) \to A^0\gamma$
$<1.3 \times 10^{-3}$	90	0	[27] ALBRECHT 86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+e^-, \gamma\gamma$)
$<2. \times 10^{-3}$	90		[28] BOWCOCK 86	CLEO	$\Upsilon(2S) \to \Upsilon(1S) \to A^0$
$<5. \times 10^{-3}$	90		[29] MAGERAS 86	CUSB	$\Upsilon(1S) \to A^0\gamma$
$<3. \times 10^{-4}$	90		[30] ALAM 83	CLEO	$\Upsilon(1S) \to A^0\gamma$
$<9.1 \times 10^{-4}$	90		[31] NICZYPORUK 83	LENA	$\Upsilon(1S) \to A^0\gamma$
$<1.4 \times 10^{-5}$	90		[32] EDWARDS 82	CBAL	$J/\psi \to A^0\gamma$
$<3.5 \times 10^{-4}$	90		[33] SIVERTZ 82	CUSB	$\Upsilon(1S) \to A^0\gamma$
$<1.2 \times 10^{-4}$	90		[33] SIVERTZ 82	CUSB	$\Upsilon(3S) \to A^0\gamma$

[20] BALEST 95 looked for a monochromatic γ from $\Upsilon(1S)$ decay. The bound is for $m_{A^0} <$ 5.0 GeV. See Fig. 7 in the paper for bounds for heavier m_{A^0}. They also quote a bound on branching ratios 10^{-3}–10^{-5} of three-body decay $\gamma X\overline{X}$ for $0 < m_X < 3.1$ GeV.

[21] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon, J/\psi$) is the reduction factor for $\Gamma(V \to A^0\gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \to ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \to ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

[22] The first DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 3 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[23] The second DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 5 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[24] The third DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} > 7 \times 10^{-12}$ s/MeV and $m_{A^0} < 200$ MeV.

[25] $\tau_{A^0} < 1 \times 10^{-13}$s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \to \gamma\gamma$ when $m_{A^0} < 100$ MeV.

[26] $\tau_{A^0} > 1 \times 10^{-7}$s.

[27] Independent of τ_{A^0}.

[28] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to A^0\gamma$. The limit for $B(\Upsilon(1S) \to A^0\gamma)B(A^0 \to e^+e^-)$ depends on m_{A^0} and τ_{A^0}. The quoted limit for m_{A^0}=1.8 MeV is at $\tau_{A^0} \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m_e < m_{A^0} < 2m_\mu$ when the results of this experiment are combined with the results of ALAM 83.

[29] MAGERAS 86 looked for $\Upsilon(1S) \to \gamma A^0$ ($A^0 \to e^+e^-$). The quoted branching fraction limit is for $m_{A^0} = 1.7$ MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$s where the limit is the worst.

[30] ALAM 83 is at CESR. This limit combined with limit for $B(J/\psi \to A^0\gamma)$ (EDWARDS 82) excludes standard axion.

[31] NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $B(\Upsilon \to A^0\gamma)$ derived from $B(J/\psi(1S) \to A^0\gamma)$ limit (EDWARDS 82) excludes standard axion.

[32] EDWARDS 82 looked for $J/\psi \to \gamma A^0$ decays by looking for events with a single γ [of energy $\sim$ 1/2 the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

[33] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \to \gamma A^0$, A^0 undetected. Limit for $1S$ ($3S$) is valid for $m_{A^0} <$7 GeV (4 GeV).

A^0 (Axion) Searches in Positronium Decays

Decay or transition of positronium. Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-4}$	90	MAENO 95	CNTR	o-Ps $\to A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0 \times 10^{-3}$	90	[34] ASAI 94	CNTR	o-Ps $\to A^0\gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[35] AKOPYAN 91	CNTR	o-Ps $\to A^0\gamma$ ($A^0 \to \gamma\gamma$), $m_{A^0} < 30$ keV
$<1.1 \times 10^{-6}$	90	[36] ASAI 91	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} < 800$ keV
$<3.8 \times 10^{-4}$	90	GNINENKO 90	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} <$ 30 keV
$<(1-5) \times 10^{-4}$	95	[37] TSUCHIAKI 90	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} =$ 300–900 keV
$<6.4 \times 10^{-5}$	90	[38] ORITO 89	CNTR	o-Ps $\to A^0\gamma$, $m_{A^0} < 30$ keV
		[39] AMALDI 85	CNTR	Ortho-positronium
		[40] CARBONI 83	CNTR	Ortho-positronium

[34] The ASAI 94 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

[35] The AKOPYAN 91 limit applies for a short-lived A^0 with $\tau_{A^0} < 10^{-13}\, m_{A^0}$ [keV] s.

[36] ASAI 91 limit translates to $g^2_{A^0 e^+ e^-}/4\pi < 1.1 \times 10^{-11}$ (90%CL) for $m_{A^0} < 800$ keV.

[37] The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

[38] ORITO 89 limit translates to $g^2_{A^0 ee}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger m_{A^0}: $B < 7.6 \times 10^{-6}$ at 100 keV.

[39] AMALDI 85 set limits $B(A^0\gamma)$ / $B(\gamma\gamma\gamma) < (1-5) \times 10^{-6}$ for m_{A^0} = 900–100 keV which are about 1/10 of the CARBONI 83 limits.

[40] CARBONI 83 looked for orthopositronium $\to A^0\gamma$. Set limit for A^0 electron coupling squared, $g(eeA^0)^2/(4\pi) < 6. \times 10^{-10}$–$7. \times 10^{-9}$ for m_{A^0} from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from $g-2$ experiments.

A^0 (Axion) Search in Photoproduction

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[41] BASSOMPIE... 95	$m_{A^0} = 1.8 \pm 0.2$ MeV

[41] BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of e^+e^- pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate A^0 for $\tau(A^0) = 10^{-18}$–10^{-9} sec. They also found an excess of events in the range $m_{e^+e^-}$ = 2.1–3.5 MeV.

A^0 (Axion) Production in Hadron Collisions

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[42] AHMAD 97	SPEC	e^+ production
			[43] LEINBERGER 97	SPEC	$A^0 \to e^+e^-$
			[44] GANZ 96	SPEC	$A^0 \to e^+e^-$
			[45] KAMEL 96	EMUL	^{32}S emulsion, $A^0 \to e^+e^-$
			[46] BLUEMLEIN 92	BDMP	$A^0 N_Z \to \ell^+\ell^- N_Z$
			[47] MEIJERDREES 92	SPEC	$\pi^- p \to nA^0$, $A^0 \to e^+e^-$
			[48] BLUEMLEIN 91	BDMP	$A^0 \to e^+e^-, 2\gamma$
			[49] FAISSNER 89	OSPK	Beam dump, $A^0 \to e^+e^-$
			[50] DEBOER 88	RVUE	$A^0 \to e^+e^-$
			[51] EL-NADI 88	EMUL	$A^0 \to e^+e^-$
			[52] FAISSNER 88	OSPK	Beam dump, $A^0 \to 2\gamma$
			[53] BADIER 86	BDMP	$A^0 \to e^+e^-$
$<2. \times 10^{-11}$	90	0	[54] BERGSMA 85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[54] BERGSMA 85	CHRM	CERN beam dump
		24	[55] FAISSNER 83	OSPK	Beam dump, $A^0 \to 2\gamma$
			[56] FAISSNER 83B	RVUE	LAMPF beam dump
			[57] FRANK 83B	RVUE	LAMPF beam dump
			[58] HOFFMAN 83	CNTR	$\pi p \to nA^0$ ($A^0 \to e^+e^-$)
			[59] FETSCHER 82	RVUE	See FAISSNER 81B
		12	[60] FAISSNER 81	OSPK	CERN PS ν wideband
		15	[61] FAISSNER 81B	OSPK	Beam dump, $A^0 \to 2\gamma$
		8	[62] KIM 81	OSPK	26 GeV $pN \to A^0X$
		0	[63] FAISSNER 80	OSPK	Beam dump, $A^0 \to e^+e^-$
$<1. \times 10^{-8}$	90		[64] JACQUES 80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[64] JACQUES 80	HLBC	Beam dump
			[65] SOUKAS 80	CALO	28 GeV p beam dump
			[66] BECHIS 79	CNTR	
$<1. \times 10^{-8}$	90		[67] COTEUS 79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[68] DISHAW 79	CALO	400 GeV pp
$<1. \times 10^{-8}$	90		ALIBRAN 78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN 78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[69] BELLOTTI 78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[69] BELLOTTI 78	HLBC	m_{A^0}=1.5 MeV
$<4.1 \times 10^{-9}$	90		[69] BELLOTTI 78	HLBC	m_{A^0}=1 MeV
$<1. \times 10^{-8}$	90		[70] BOSETTI 78B	HYBR	Beam dump
			[71] DONNELLY 78		
$<0.5 \times 10^{-8}$	90		HANSL 78D	WIRE	Beam dump
			[72] MICELMAC... 78		
			[73] VYSOTSKII 78		

[42] AHMAD 97 reports a result of APEX Collaboration which studied positron production in ^{238}U+^{232}Ta and ^{238}U+^{181}Ta collisions, without requiring a coincident electron. No narrow lines were found for $250 < E_{e^+} < 750$ keV.

[43] LEINBERGER 97 (ORANGE Collaboration) at GSI looked for a narrow sum-energy e^+e^--line at $\sim$ 635 keV in ^{238}U+^{181}Ta collision. Limits on the production probability for a narrow sum-energy e^+e^- line are set. See their Table 2.

[44] GANZ 96 (EPos II Collaboration) has placed upper bounds on the production cross section of e^+e^- pairs from ^{238}U+^{181}Ta and ^{238}U+^{232}Th collisions at GSI. See Table 2 for limits both for back-to-back and isotropic configurations of e^+e^- pairs. These limits rule out the existence of peaks in the e^+e^- sum-energy distribution, reported by an earlier version of this experiment.

[45] KAMEL 96 looked for e^+e^- pairs from the collison of ^{32}S (200 GeV/nucleon) and emulsion. No evidence of mass peaks is found in the region of sensitivity $m_{ee} >$2 MeV.

[46] BLUEMLEIN 92 is a proton beam dump experiment at Serpukhov with a secondary target to induce Bethe-Heitler production of e^+e^- or $\mu^+\mu^-$ from the produce A^0. See Fig. 5 for the excluded region in m_{A^0}-x plane. For the standard axion, $0.3 < x < 25$ is excluded at 95% CL. If combined with BLUEMLEIN 91, $0.008 < x < 32$ is excluded.

[47] MEIJERDREES 92 give $\Gamma(\pi^- p \to nA^0)\cdot B(A^0 \to e^+e^-)/\Gamma(\pi^- p \to \text{all}) < 10^{-5}$ (90% CL) for $m_{A^0} = 100$ MeV, $\tau_{A^0} = 10^{-11}$–10^{-23} sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for $m_{A^0} = 25$–136 MeV.

[48] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \to e^+e^-$, 2γ are found. Fig. 6 gives the excluded region in m_{A^0}-x plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m_{A^0} < 3.2$ MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$.

[49] FAISSNER 89 searched for $A^0 \to e^+e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m_e$–20 MeV is excluded. Lower limit on f_{A^0} of $\simeq 10^4$ GeV is given for $m_{A^0} = 2m_e$–20 MeV.

[50] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass ~ 1.1, ~ 2.1, and ~ 9 MeV, lifetimes 10^{-16}–10^{-15} s decaying to e^+e^- and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism.

[51] EL-NADI 88 claim the existence of a neutral particle decaying into e^+e^- with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at ~ 4 GeV/c/nucleon.

[52] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \to \gamma\gamma$. A standard axion decaying to 2γ is excluded except for a region $x \simeq 1$. Lower limit on f_{A^0} of 10^2–10^3 GeV is given for $m_{A^0} = 0.1$–1 MeV.

[53] BADIER 86 did not find long-lived A^0 in 300 GeV π^- Beam Dump Experiment that decays into e^+e^- in the mass range $m_{A^0} = (20$–$200)$ MeV, which excludes the A^0 decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-m_{A^0} plane.

[54] BERGSMA 85 look for $A^0 \to 2\gamma$, e^+e^-, $\mu^+\mu^-$. First limit above is for $m_{A^0} = 1$ MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0} - m_{A^0}$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, $m_{A^0} < 180$ keV and $\tau > 0.037$ s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[55] FAISSNER 83 observed 19 1-γ and 12 2-γ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

[56] FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ's are not at variance with LAMPF upper limit of 450 γ's. Derived from LAMPF limit that $[d\sigma(A^0)/d\omega \text{ at } 90^\circ] m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[57] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 γ's. See comment on FAISSNER 83B.

[58] HOFFMAN 83 set CL = 90% limit $d\sigma/dt\, B(e^+e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for $140 < m_{A^0} < 160$ MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[59] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-γ peak rate remarkably decreases if iron wall is set in front of the decay region.

[60] FAISSNER 81 see excess μe events. Suggest axion interactions.

[61] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with η-A^0 mixing gives $m_{A^0} = 250 \pm 25$ keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[62] KIM 81 analyzed 8 candidates for $A^0 \to 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86 \sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[63] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \to e^+e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/(A^0 mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

[64] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interactaction}) < 7. \times 10^{-68}$ cm^4, CL = 90%$]$. Second limit is from nonobservation of axion decays into 2γ's or e^+e^-, and for axion mass a few MeV.

[65] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[66] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2γ or e^+e^-. No signal found. CL = 90% limits for model parameter(s) are given.

[67] COTEUS 79 is a beam dump experiment at BNL.

[68] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[69] BELLOTTI 78 first value comes from search for $A^0 \to e^+e^-$. Second value comes from search for $A^0 \to 2\gamma$, assuming mass $< 2m_{e^-}$. For any mass satisfying this, limit is above value$\times$(mass^{-4}). Third value uses data of PL 60B 401 and quotes $\sigma(\text{production})\sigma(\text{interaction}) < 10^{-67}$ cm^4.

[70] BOSETTI 78B quotes $\sigma(\text{production})\sigma(\text{interaction}) < 2. \times 10^{-67}$ cm^4.

[71] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[72] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[73] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

A^0 (Axion) Searches in Reactor Experiments

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[74] ALTMANN 95	CNTR	Reactor; $A^0 \to e^+e^-$
	[75] KETOV 86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[76] KOCH 86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[77] DATAR 82	CNTR	Light water reactor
	[78] VUILLEUMIER 81	CNTR	Reactor, $A^0 \to 2\gamma$

[74] ALTMANN 95 looked for A^0 decaying into e^+e^- from the Bugey 5 nuclear reactor. They obtain an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma) \times B(A^0 \to e^+e^-) < 10^{-16}$ for $m_{A^0} = 1.5$ MeV at 90% CL. The limit is weaker for heavier A^0. In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances Z^0 in the (m_{X^0}, f_{X^0}) plane.

[75] KETOV 86 searched for A^0 at the Rovno nuclear power plant. They found an upper limit on the A^0 production probability of $0.8\,[100\text{ keV}/m_{A^0}]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to $m_{A^0} > 150$ keV. Not valid for $m_{A^0} \gtrsim 1$ MeV.

[76] KOCH 86 searched for $A^0 \to \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m_{A^0} = 250$ keV gives 10^{-5} for the ratio. Not valid for $m_{A^0} > 1022$ keV.

[77] DATAR 82 looked for $A^0 \to 2\gamma$ in neutron capture ($np \to dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I = 0) - (I = 1)]$ result, assert nonexistence of standard A^0.

[78] VUILLEUMIER 81 is at Grenoble reactor. Set limit $m_{A^0} < 280$ keV.

A^0 (Axion) and Other Light Boson (X^0) Searches in Nuclear Transitions

Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[79] DEBOER 97C	RVUE	M1 transitions
$< 5.5 \times 10^{-10}$	95		[80] TSUNODA 95	CNTR	^{252}Cf fission, $A^0 \to ee$
$< 1.2 \times 10^{-6}$	95		[81] MINOWA 93	CNTR	$^{139}\text{La}^* \to {}^{139}\text{La}A^0$
$< 2 \times 10^{-4}$	90		[82] HICKS 92	CNTR	^{35}S decay, $A^0 \to \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[83] ASANUMA 90	CNTR	^{241}Am decay
$<(0.4$–$10) \times 10^{-3}$	95		[84] DEBOER 90	CNTR	$^8\text{Be}^* \to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$
$<(0.2$–$1) \times 10^{-3}$	90		[85] BINI 89	CNTR	$^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
			[86] AVIGNONE 88	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[87] DATAR 88	CNTR	$^{12}\text{C}^* \to {}^{12}\text{C}A^0$, $A^0 \to e^+e^-$
$< 5 \times 10^{-3}$	90		[88] DEBOER 88C	CNTR	$^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
$< 3.4 \times 10^{-5}$	95		[89] DOEHNER 88	SPEC	$^2\text{H}^*$, $A^0 \to e^+e^-$
$< 4 \times 10^{-4}$	95		[90] SAVAGE 88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[90] SAVAGE 88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[91] HALLIN 86	SPEC	^{6}Li isovector decay
<10.8	90		[91] HALLIN 86	SPEC	^{10}B isoscalar decays
< 2.2	90		[91] HALLIN 86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[92] SAVAGE 86B	CNTR	$^{14}\text{N}^*$
			[93] ANANEV 85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[94] CAVAIGNAC 83	CNTR	$^{97}\text{Nb}^*$, deut* transition $A^0 \to 2\gamma$
			[95] ALEKSEEV 82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[96] LEHMANN 82	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$)
		0	[97] ZEHNDER 82	CNTR	Li*, Nb* decay, n-capt.
		0	[98] ZEHNDER 81	CNTR	$\text{Ba}^* \to \text{Ba}A^0$ ($A^0 \to 2\gamma$)
			[99] CALAPRICE 79		Carbon

[79] DEBOER 97C reanalyzed the existent data on Nuclear M1 transitions and find that a 9 MeV boson decaying into e^+e^- would explain the excess of events with large opening angles.

[80] TSUNODA 95 looked for axion emission when ^{252}Cf undergoes a spontaneous fission, with the axion decaying into e^+e^-. The bound is for m_{A^0}=40 MeV. It improves to 2.5×10^{-5} for m_{A^0}=200 MeV.

[81] MINOWA 93 studied chain process, $^{139}\text{Ce} \to {}^{139}\text{La}^*$ by electron capture and M1 transition of $^{139}\text{La}^*$ to the ground state. It does not assume decay modes of A^0. The bound applies for $m_{A^0} < 166$ keV.

[82] HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec.

[83] The ASANUMA 90 limit is for the branching fraction of X^0 emission per $^{241}\text{Am}\,\alpha$ decay and valid for $\tau_{X^0} < 3 \times 10^{-11}$ s.

[84] The DEBOER 90 limit is for the branching ratio $^8\text{Be}^*$ (18.15 MeV, 1^+) $\to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$ for the mass range $m_{A^0} = 4$–15 MeV.

[85] The BINI 89 limit is for the branching fraction of $^{16}\text{O}^*$(6.05 MeV, 0^+) $\to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ for $m_X = 1.5$–3.1 MeV. $\tau_{X^0} \lesssim 10^{-11}$ s is assumed. The spin-parity of X is restricted to 0^+ or 1^-.

[86] AVIGNONE 88 looked for the 1115 keV transition $C^* \to \text{Cu}A^0$, either from $A^0 \to 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV.

[87] DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \to e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range 10^{-13}–10^{-8} s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m = 1.7$ MeV; see the paper for the τ-m dependence of the limit.

[88] The limit is for the branching fraction of ${}^{16}\text{O}^*(6.05\ \text{MeV}, 0^+) \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ against internal pair conversion for $m_{X^0} = 1.7$ MeV and $\tau_{X^0} < 10^{-11}$ s. Similar limits are obtained for $m_{X^0} = 1.3$–3.2 MeV. The spin parity of X^0 must be either 0^+ or 1^-. The limit at 1.7 MeV is translated into a limit for the X^0-nucleon coupling constant: $g^2_{X^0NN}/4\pi < 2.3 \times 10^{-9}$.

[89] The DOEHNER 88 limit is for $m_{A^0} = 1.7$ MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than 10^{-4} are obtained for $m_{A^0} = 1.2$–2.2 MeV.

[90] SAVAGE 88 looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N, 17.64 MeV state $J^P = 1^+$ in ^{8}Be, and the 18.15 MeV state $J^P = 1^+$ in ^{8}Be. This experiment constrains the isovector coupling of A^0 to hadrons, if $m_{A^0} = (1.1 \to 2.2)$ MeV and the isoscalar coupling of A^0 to hadrons, if $m_{A^0} = (1.1 \to 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[91] Limits are for $\Gamma(A^0(1.8\ \text{MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of e^+e^- pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$s. ^{6}Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the ^{10}B and ^{14}N isoscalar decay data strongly reject PECCEI 86 model II and III.

[92] SAVAGE 86B looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N. Limit on the branching fraction is valid if $\tau_{A^0} \lesssim 1. \times 10^{-11}$s for $m_{A^0} = (1.1$–$1.7)$ MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.

[93] ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li* decay) and below $2m_e$ for deuteron* decay.

[94] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m_{{}^{97}\text{Nb}^*\text{decay}}$ and axion with m_{A^0} between 275 and 288 keV (deuteron* decay).

[95] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges m_{A^0} <400 keV (Li* decay) and 330 keV $< m_{A^0} <$2.2 MeV. (deuteron* decay).

[96] LEHMANN 82 obtained $A^0 \to 2\gamma$ rate $< 6.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} between 100 and 1000 keV.

[97] ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li*, Nb* decay (both single p transition) nor in n capture (combined with previous Ba* negative result) rules out standard A^0. Set limit m_{A^0} <60 keV for any A^0.

[98] ZEHNDER 81 looked for $\text{Ba}^* \to A^0\text{Ba}$ transition with $A^0 \to 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[99] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

Limits are for $\tau(A^0 \to e^+e^-)$.

VALUE (s)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 4×10^{-16}–4.5×10^{-12}	90	[100] BROSS 91	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[101] GUO 90	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
		[102] BJORKEN 88	CALO	$A \to e^+e^-$ or 2γ
		[103] BLINOV 88	MD1	$ee \to eeA^0$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-10}	90	[104] RIORDAN 87	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 1×10^{-14}–1×10^{-11}	90	[105] BROWN 86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 6×10^{-14}–9×10^{-11}	95	[106] DAVIER 86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$
none 3×10^{-13}–1×10^{-7}	90	[107] KONAKA 86	BDMP	$eN \to eA^0N$ $(A^0 \to ee)$

[100] The listed BROSS 91 limit is for $m_{A^0} = 1.14$ MeV. $B(A^0 \to e^+e^-) = 1$ assumed. Excluded domain in the τ_{A^0}–m_{A^0} plane extends up to $m_{A^0} \approx 7$ MeV (see Fig. 5). Combining with electron $g-2$ constraint, axions coupling only to e^+e^- ruled out for $m_{A^0} < 4.8$ MeV (90%CL).

[101] GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with $g-2$ constraint, axions coupling only to e^+e^- are ruled out for $m_{A^0} < 2.7$ MeV (90% CL).

[102] BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_A) for $m_{A^0} < 200$ MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

[103] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5 \times 10^{-12}$ s and find $\Gamma(A^0 \to \gamma\gamma)B(A^0 \to e^+e^-) < 2$ eV (CL=90%).

[104] Assumes $A^0\gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for $m_{A^0} < 15$ MeV.

[105] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for $m_{A^0} < 15$ MeV are shown in their figure 3.

[106] $m_{A^0} \simeq 1.8$ MeV assumed. The excluded domain in the $\tau_{A^0}-m_{A^0}$ plane extends up to $m_{A^0} \approx 14$ MeV, see their figure 4.

[107] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$–$A^0e^+e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha Scattering

The limit is for $\Gamma(A^0)[B(A^0 \to e^+e^-)]^2$.

VALUE (10^{-3} eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 1.3	97	[108] HALLIN 92	CNTR	$m_{A^0} = 1.75$–1.88 MeV
none 0.0016–0.47	90	[109] HENDERSON 92C	CNTR	$m_{A^0} = 1.5$–1.86 MeV
< 2.0	90	[110] WU 92	CNTR	$m_{A^0} = 1.56$–1.86 MeV
< 0.013	95	TSERTOS 91	CNTR	$m_{A^0} = 1.832$ MeV
none 0.19–3.3	95	[111] WIDMANN 91	CNTR	$m_{A^0} = 1.78$–1.92 MeV
< 5	97	BAUER 90	CNTR	$m_{A^0} = 1.832$ MeV
none 0.09–1.5	95	[112] JUDGE 90	CNTR	$m_{A^0} = 1.832$ MeV, elastic
< 1.9	97	[113] TSERTOS 89	CNTR	$m_{A^0} = 1.82$ MeV
<(10–40)	97	[113] TSERTOS 89	CNTR	$m_{A^0} = 1.51$–1.65 MeV
<(1–2.5)	97	[113] TSERTOS 89	CNTR	$m_{A^0} = 1.80$–1.86 MeV
< 31	95	LORENZ 88	CNTR	$m_{A^0} = 1.646$ MeV
< 94	95	LORENZ 88	CNTR	$m_{A^0} = 1.726$ MeV
< 23	95	LORENZ 88	CNTR	$m_{A^0} = 1.782$ MeV
< 19	95	LORENZ 88	CNTR	$m_{A^0} = 1.837$ MeV
< 3.8	97	[114] TSERTOS 88	CNTR	$m_{A^0} = 1.832$ MeV
		[115] VANKLINKEN 88	CNTR	
		[116] MAIER 87	CNTR	
<2500	90	MILLS 87	CNTR	$m_{A^0} = 1.8$ MeV
		[117] VONWIMMER.87	CNTR	

[108] HALLIN 92 quote limits on lifetime, $8 \times 10^{-14} - 5 \times 10^{-13}$ sec depending on mass, assuming $B(A^0 \to e^+e^-) = 100\%$. They say that TSERTOS 91 overstated their sensitivity by a factor of 3.

[109] HENDERSON 92C exclude axion with lifetime $\tau_{A^0} = 1.4 \times 10^{-12} - 4.0 \times 10^{-10}$ s, assuming $B(A^0 \to e^+e^-) = 100\%$. HENDERSON 92C also exclude a vector boson with $\tau = 1.4 \times 10^{-12} - 6.0 \times 10^{-10}$ s.

[110] WU 92 quote limits on lifetime $> 3.3 \times 10^{-13}$ s assuming $B(A^0 \to e^+e^-) = 100\%$. They say that TSERTOS 89 overestimate the limit by a factor of $\pi/2$. WU 92 also quote a bound for vector boson, $\tau > 8.2 \times 10^{-13}$ s.

[111] WIDMANN 91 bound applies exclusively to the case $B(A^0 \to e^+e^-) = 1$, since the detection efficiency varies substantially as $\Gamma(A^0)_{\text{total}}$ changes. See their Fig. 6.

[112] JUDGE 90 excludes an elastic pseudoscalar e^+e^- resonance for $4.5 \times 10^{-13}\ \text{s} < \tau(A^0) < 7.5 \times 10^{-12}$ s (95% CL) at $m_{A^0} = 1.832$ MeV. Comparable limits can be set for $m_{A^0} = 1.776$–1.856 MeV.

[113] See also TSERTOS 88B in references.

[114] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

[115] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}$–10^{-12} s). The sensitivity is not sufficient to exclude such a narrow resonance.

[116] MAIER 87 obtained limits $R\Gamma \lesssim 60$ eV (100 eV) at $m_{A^0} \simeq 1.64$ MeV (1.83 MeV) for energy resolution $\Delta E_{\text{cm}} \simeq 3$ keV, where R is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma^2_{ee}/\Gamma_{\text{total}}$. For a discussion implying that $\Delta E_{\text{cm}} \simeq 10$ keV, see TSERTOS 89.

[117] VONWIMMERSPERG 87 measured Bhabha scattering for $E_{\text{cm}} = 1.37$–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}} = 14.5 \pm 6.8$ keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.

Search for A^0 (Axion) Resonance in $e^+e^- \to \gamma\gamma$

The limit is for $\Gamma(A^0 \to e^+e^-) \cdot \Gamma(A^0 \to \gamma\gamma)/\Gamma_{\text{total}}$

VALUE (10^{-3} eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.18	95	VO 94	CNTR	$m_{A^0} = 1.1$ MeV
< 1.5	95	VO 94	CNTR	$m_{A^0} = 1.4$ MeV
<12	95	VO 94	CNTR	$m_{A^0} = 1.7$ MeV
< 6.6	95	[118] TRZASKA 91	CNTR	$m_{A^0} = 1.8$ MeV
< 4.4	95	WIDMANN 91	CNTR	$m_{A^0} = 1.78$–1.92 MeV
		[119] FOX 89	CNTR	
< 0.11	95	[120] MINOWA 89	CNTR	$m_{A^0} = 1.062$ MeV
<33	97	CONNELL 88	CNTR	$m_{A^0} = 1.580$ MeV
<42	97	CONNELL 88	CNTR	$m_{A^0} = 1.642$ MeV
<73	97	CONNELL 88	CNTR	$m_{A^0} = 1.782$ MeV
<79	97	CONNELL 88	CNTR	$m_{A^0} = 1.832$ MeV

[118] TRZASKA 91 also give limits in the range $(6.6$–$30) \times 10^{-3}$ eV (95%CL) for $m_{A^0} = 1.6$–2.0 MeV.

[119] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($< 9 \times 10^{-5}$ of two-photon annihilation at rest).

[120] Similar limits are obtained for $m_{A^0} = 1.045$–1.085 MeV.

Search for X^0 (Light Boson) Resonance in $e^+e^- \rightarrow \gamma\gamma\gamma$

The limit is for $\Gamma(X^0 \rightarrow e^+e^-)\cdot\Gamma(X^0 \rightarrow \gamma\gamma\gamma)/\Gamma_{total}$. C invariance forbids spin-0 X^0 coupling to both e^+e^- and $\gamma\gamma\gamma$.

VALUE (10^{-3} eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.2	95	[121] VO 94	CNTR	m_{X^0}=1.1–1.9 MeV
< 1.0	95	[122] VO 94	CNTR	m_{X^0}=1.1 MeV
< 2.5	95	[122] VO 94	CNTR	m_{X^0}=1.4 MeV
<120	95	[122] VO 94	CNTR	m_{X^0}=1.7 MeV
< 3.8	95	[123] SKALSEY 92	CNTR	m_{X^0}= 1.5 MeV

[121] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying at rest. The precise limits depend on m_{X^0}. See Fig. 2(b) in paper.

[122] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.

[123] SKALSEY 92 also give limits 4.3 for $m_{X^0} = 1.54$ and 7.5 for 1.64 MeV. The spin of X^0 is assumed to be one.

Light Boson (X^0) Search in Nonresonant e^+e^- Annihilation at Rest

Limits are for the ratio of $n\gamma + X^0$ production relative to $\gamma\gamma$.

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.2	90	[124] MITSUI 96	CNTR	γX^0
< 4	68	[125] SKALSEY 95	CNTR	γX^0
<40	68	[126] SKALSEY 95	RVUE	γX^0
< 0.18	90	[127] ADACHI 94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$
< 0.26	90	[128] ADACHI 94	CNTR	$\gamma\gamma X^0$, $X^0 \rightarrow \gamma\gamma$
< 0.33	90	[129] ADACHI 94	CNTR	γX^0, $X^0 \rightarrow \gamma\gamma\gamma$

[124] MITSUI 96 looked for a monochromatic γ. The bound applies for a vector X^0 with $C=-1$ and m_{X^0} <200 keV. They derive an upper bound on eeX^0 coupling and hence on the branching ratio B(o-Ps $\rightarrow \gamma\gamma X^0$)< 6.2×10^{-6}. The bounds weaken for heavier X^0.

[125] SKALSEY 95 looked for a monochromatic γ without an accompanying γ in e^+e^- annihilation. The bound applies for scalar and vector X^0 with $C = -1$ and m_{X^0} = 100–1000 keV.

[126] SKALSEY 95 reinterpreted the bound on γA^0 decay of o-Ps by ASAI 91 where 3% of delayed annihilations are not from $^3S_1$ states. The bound applies for scalar and vector X^0 with $C = -1$ and m_{X^0} = 0–800 keV.

[127] ADACHI 94 looked for a peak in the $\gamma\gamma$ invariant mass distribution in $\gamma\gamma\gamma\gamma$ production from e^+e^- annihilation. The bound applies for m_{X^0} = 70–800 keV.

[128] ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from e^+e^- annihilation. The bound applies for m_{X^0} <800 keV.

[129] ADACHI 94 looked for a peak in the missing mass distribution in $\gamma\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from e^+e^- annihilation. The bound applies for m_{X^0} = 200–900 keV.

Searches for Goldstone Bosons (X^0)

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[130] BOBRAKOV 91		Electron quasi-magnetic interaction
$<3.3 \times 10^{-2}$	95		[131] ALBRECHT 90E	ARG	$\tau \rightarrow \mu X^0$. Familon
$<1.8 \times 10^{-2}$	95		[131] ALBRECHT 90E	ARG	$\tau \rightarrow eX^0$. Familon
$<6.4 \times 10^{-9}$	90		[132] ATIYA 90	B787	$K^+ \rightarrow \pi^+ X^0$. Familon
$<1.1 \times 10^{-9}$	90		[133] BOLTON 88	CBOX	$\mu^+ \rightarrow e^+ \gamma X^0$. Familon
			[134] CHANDA 88	ASTR	Sun, Majoron
			[135] CHOI 88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90		[136] PICCIOTTO 88	CNTR	$\pi \rightarrow e\nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90		[137] GOLDMAN 87	CNTR	$\mu \rightarrow e\gamma X^0$. Familon
$<3 \times 10^{-4}$	90		[138] BRYMAN 86B	RVUE	$\mu \rightarrow eX^0$. Familon
$<1. \times 10^{-10}$	90	0	[139] EICHLER 86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
$<2.6 \times 10^{-6}$	90		[140] JODIDIO 86	SPEC	$\mu^+ \rightarrow e^+ X^0$. Familon
			[141] BALTRUSAIT...85	MRK3	$\tau \rightarrow \ell X^0$. Familon
			[142] DICUS 83	COSM	ν(hvy) $\rightarrow \nu$(light)X^0

[130] BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $x_e^2 < 2 \times 10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $x_e(G_F/8\pi\sqrt{2})^{1/2}$.

[131] ALBRECHT 90E limits are for B($\tau \rightarrow \ell X^0$)/B($\tau \rightarrow \ell\nu\overline{\nu}$). Valid for m_{X^0} < 100 MeV. The limits rise to 7.1% (for μ), 5.0% (for e) for m_{X^0} = 500 MeV.

[132] ATIYA 90 limit is for $m_{X^0} = 0$. The limit B < 1×10^{-8} holds for m_{X^0} < 95 MeV. For the reduction of the limit due to finite lifetime of X^0, see their Fig. 3.

[133] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.

[134] CHANDA 88 find v_T < 10 MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.

[135] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{int} = \frac{1}{2} l h \overline{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_l^4)^{1/4}$.

[136] PICCIOTTO 88 limit applies when m_{X^0} < 55 MeV and τ_{X^0} > 2ns, and it decreases to 4×10^{-7} at m_{X^0} = 125 MeV, beyond which no limit is obtained.

[137] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{int} = (1/F)\overline{\psi}_\mu \gamma^\mu (a+b\gamma_5) \psi_e \partial_\mu \phi_{X^0}$ with $a^2+b^2 = 1$. This is not as sensitive as the limit $F > 9.9 \times 10^9$ GeV derived from the search for $\mu^+ \rightarrow e^+ X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

[138] Limits are for $\Gamma(\mu \rightarrow eX^0)/\Gamma(\mu \rightarrow e\nu\overline{\nu})$. Valid when m_{X^0} = 0–93.4, 98.1–103.5 MeV.

[139] EICHLER 86 looked for $\mu^+ \rightarrow e^+ X^0$ followed by $X^0 \rightarrow e^+e^-$. Limits on the branching fraction depend on the mass and and lifetime of X^0. The quoted limits are valid when $\tau_{X^0} \lesssim 3. \times 10^{-10}$ s if the decays are kinematically allowed.

[140] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{int} = (1/F)\, \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.

[141] BALTRUSAITIS 85 search for light Goldstone boson(X^0) of broken U(1). CL = 95% limits are B($\tau \rightarrow \mu^+ X^0$)/B($\tau \rightarrow \mu^+ \nu\nu$) <0.125 and B($\tau \rightarrow e^+ X^0$)/B($\tau \rightarrow e^+ \nu\nu$) <0.04. Inferred limit for the symmetry breaking scale is m >3000 TeV.

[142] The primordial heavy neutrino must decay into ν and familon, f_A, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \rightarrow \pi f_A$ and $\mu \rightarrow e f_A$ are unseen. Combining these excludes $m_{\text{heavy}\nu}$ between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\text{heavy}\nu}$ between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission. Previous indications for neutrinoless double beta decay with majoron emission have been superseded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 7.2 × 10^{24}	90	[143] BERNATOW... 92	CNTR	^{128}Te
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 7.91 × 10^{21}	90	[144] GUENTHER 96	SPEC	^{76}Ge
> 1.7 × 10^{22}	90	BECK 93	CNTR	^{76}Ge
> 7.9 × 10^{20}	68	[145] TANAKA 93	SPEC	^{100}Mo
> 1.9 × 10^{20}	68	BARABASH 89	CNTR	^{136}Xe
> 1.0 × 10^{21}	90	FISHER 89	CNTR	^{76}Ge
> 3.3 × 10^{20}	90	ALSTON-... 88	CNTR	^{100}Mo
(6 ±1) × 10^{20}		AVIGNONE 87	CNTR	^{76}Ge
> 1.4 × 10^{21}	90	CALDWELL 87	CNTR	^{76}Ge
> 4.4 × 10^{20}	90	ELLIOTT 87	SPEC	^{82}Se
> 1.2 × 10^{21}	90	FISHER 87	CNTR	^{76}Ge
		[146] VERGADOS 82	CNTR	

[143] BERNATOWICZ 92 studied double-β decays of ^{128}Te and ^{130}Te, and found the ratio $\tau(^{130}\text{Te})/\tau(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$ in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of ^{128}Te of $(7.7 \pm 0.4) \times 10^{24}$ year. We calculated 90% CL limit as $(7.7-1.28 \times 0.4=7.2) \times 10^{24}$.

[144] See Table 1 in GUENTHER 96 for limits on the Majoron coupling in different models.

[145] TANAKA 93 also quote limit 5.3×10^{19} years on two Majoron emission.

[146] VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H, of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca.

Invisible A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$ is usually assumed (v_i = vacuum expectation values). For a review of these limits, see RAFFELT 90C and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

VALUE (eV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 0.007	[147] BORISOV 97	ASTR	D, neutron star
< 4	[148] KACHELRIESS 97	ASTR	D, neutron star cooling
$<(0.5–6) \times 10^{-3}$	[149] KEIL 97	ASTR	SN 1987A
< 0.018	[150] RAFFELT 95	ASTR	D, red giant
< 0.010	[151] ALTHERR 94	ASTR	D, red giants, white dwarfs
< 0.01	WANG 92	ASTR	D, white dwarf
< 0.03	WANG 92C	ASTR	D, C-O burning
none 3–8	[152] BERSHADY 91	ASTR	D, K, intergalactic light
<10	[153] KIM 91C	COSM	D, K, mass density of the universe, supersymmetry
	[154] RAFFELT 91B	ASTR	D,K, SN 1987A
$< 1 \times 10^{-3}$	[155] RESSELL 91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS 90	ASTR	D,K, SN 1987A
	[156] ENGEL 90	ASTR	D,K, SN 1987A
< 0.02	[157] RAFFELT 90D	ASTR	D, red giant
$< 1 \times 10^{-3}$	[158] BURROWS 89	ASTR	D,K, SN 1987A
$<(1.4–10) \times 10^{-3}$	[159] ERICSON 89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[160] MAYLE 89	ASTR	D,K, SN 1987A
<12	CHANDA 88	ASTR	D, Sun

$< 1 \quad \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[161] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[162] RAFFELT	87	ASTR	K, red giant
< 2–5	TURNER	87	COSM	K, thermal production
< 0.01	[163] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[164] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[165] KAPLAN	85	ASTR	K, red giant
< 0.003–0.02	IWAMOTO	84	ASTR	D, K, neutron star
$> 1 \quad \times 10^{-5}$	ABBOTT	83	COSM	D,K, mass density of the universe
$> 1 \quad \times 10^{-5}$	DINE	83	COSM	D,K, mass density of the universe
< 0.04	ELLIS	83B	ASTR	D, red giant
$> 1 \quad \times 10^{-5}$	PRESKILL	83	COSM	D,K, mass density of the universe
< 0.1	BARROSO	82	ASTR	D, red giant
< 1	[166] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[147] BORISOV 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-13}$ from the photoproduction of axions off of electric fields in the outer layers of neutron stars.

[148] KACHELRIESS 97 bound is on the axion-electron coupling $g_{ae} < 1 \times 10^{-10}$ from the production of axions in strongly magnetized neutron stars. The authors also quote a stronger limit, $g_{ae} < 9 \times 10^{-13}$ which is strongly dependent on the strength of the magnetic field in white dwarfs.

[149] KEIL 97 uses new measurements of the axial-vector coupling strength of nucleons, as well as a reanalysis of many-body effects and pion-emission processes in the core of the neutron star, to update limits on the invisible-axion mass.

[150] RAFFELT 95 reexamined the constraints on axion emission from red giants due to the axion-electron coupling. They improve on DEARBORN 86 by taking into proper account degeneracy effects in the bremsstrahlung rate. The limit comes from requiring the red giant core mass at helium ignition not to exceed its standard value by more than 5% (0.025 solar masses).

[151] ALTHERR 94 bound is on the axion-electron coupling $g_{ae} < 1.5 \times 10^{-13}$, from energy loss via axion emission.

[152] BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from 2γ decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.

[153] KIM 91C argues that the bound from the mass density of the universe will change drastically for the supersymmetric models due to the entropy production of saxion (scalar component in the axionic chiral multiplet) decay. Note that it is an *upperbound* rather than a lowerbound.

[154] RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

[155] RESSELL 91 uses absence of any intracluster line emission to set limit.

[156] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to 2.5×10^{-3} eV $\lesssim m_{A^0} \lesssim 2.5 \times 10^{4}$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.

[157] RAFFELT 90D is a re-analysis of DEARBORN 86.

[158] The region $m_{A^0} \gtrsim 2$ eV is also allowed.

[159] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.

[160] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.

[161] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg g^{-1} s^{-1}, which gives a firmer basis for the axion limits based on red giant cooling.

[162] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV^{-1}.

[163] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV^{-1}.

[164] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}$ GeV^{-1} from red giants and $< 2.4\times10^{-9}$ GeV^{-1} from the sun.

[165] KAPLAN 85 says $m_{A^0} < 23$ eV is allowed for a special choice of model parameters.

[166] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV^{-1}.

Search for Relic Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m_{A^0}]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\text{int}} = \frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\tilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, and ρ_A is the axion energy density near the earth.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \quad \times 10^{-41}$		[167] HAGMANN	90	CNTR	$m_{A^0} = (5.4$–$5.9)10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[168] WUENSCH	89	CNTR	$m_{A^0} = (4.5$–$10.2)10^{-6}$ eV
$<2 \quad \times 10^{-41}$	95	[168] WUENSCH	89	CNTR	$m_{A^0} = (11.3$–$16.3)10^{-6}$ eV

[167] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.

[168] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and $\rho_A = 300$ MeV/cm^3 that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2\, \rho_A = 4 \times 10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Invisible A^0 (Axion) Limits from Photon Coupling

Limits are for the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$. Related limits from astrophysics can be found in the "Invisible A^0 (Axion) Mass Limits from Astrophysics and Cosmology" section.

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-7}$	95	[169] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[170] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[171] LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[171] LAZARUS	92	$m_{A^0} = 0.03$–0.11 eV
$<7.7 \times 10^{-7}$	99	[172] RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[173] SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

[169] Experiment based on proposal by MAIANI 86.

[170] Experiment based on proposal by VANBIBBER 87.

[171] LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.

[172] RUOSO 92 experiment is based on the proposal by VANBIBBER 87.

[173] SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to $m_{A^0} = 4 \times 10^{-3}$ where $G_{A\gamma\gamma} < 1 \times 10^{-4}$ GeV^{-1}.

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee}\partial_\mu \phi_A \overline{e}\gamma^\mu\gamma_5 e$ in GeV^{-1}, or equivalenty, the dipole-dipole potential $\frac{G^2_{Aee}}{4\pi}\left((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})\,(\boldsymbol{\sigma}_2 \cdot \boldsymbol{n})\right)/r^3$ where $\boldsymbol{n}=\boldsymbol{r}/r$.

The limits below apply to invisible axion of $m_A \leq 10^{-6}$ eV.

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.3 \times 10^{-5}$	66	[174] NI	94		Induced magnetism
$<6.7 \times 10^{-5}$	66	[174] CHUI	93		Induced magnetism
$<3.6 \times 10^{-4}$	66	[175] PAN	92		Torsion pendulum
$<2.7 \times 10^{-5}$	95	[174] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[176] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[175] RITTER	90		Torsion pendulum
$<6.6 \times 10^{-5}$	95	[174] VOROBYOV	88		Induced magnetism

[174] These experiments measured induced magnetization of a bulk material by the spin-dependent potential generated from other bulk material with aligned electron spins, where the magnetic field is shielded with superconductor.

[175] These experiments used a torsion pendulum to measure the potential between two bulk matter objects where the spins are polarized but without a net magnetic field in either of them.

[176] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

Axion Limits from *T*-violating Medium-Range Forces

The limit is for the coupling g in a T-violating potential between nucleons or nucleon and electron of the form $V = \frac{g\hbar^2}{8\pi m_p}(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\left(\frac{1}{r^2} + \frac{m_A c}{\hbar r}\right) e^{-m_A c r/\hbar}$

VALUE	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[177] YOUDIN	96

[177] YOUDIN 96 compared the precession frequencies of atomic ^{199}Hg and Cs when a large mass is positioned near the cells, relative to an applied magnetic field. See Fig. 3 for their limits.

REFERENCES FOR Searches for Axions (A^0) and Other Very Light Bosons

ADLER	97	PRL 79 2204	S. Adler+	(BNL 787 Collab.)
AHMAD	97	PRL 78 618	I. Ahmad+	(APEX Collab.)
BORISOV	97	JETP 83 868	+Grishinia	(MOSU)
DEBOER	97C	JP G23 L85	F.W.N. de Boer+	
KACHELRIESS	97	PR D56 1313	+Wilke, Wunner	(BOCH)
KEIL	97	PR D56 2419	W. Keil+	
KITCHING	97	PRL 79 4079	P. Kitching+	(BNL 787 Collab.)
LEINBERGER	97	PL B394 16	U. Leinberger+	(ORANGE Collab.)
ADLER	96	PRL 76 1421	+Atiya, Chiang, Frank, Haggerty, Kycia+	(BNL 787 Collab.)
AMSLER	96B	ZPHY C70 219	+Armstrong, Baker, Barnett+	(Crystal Barrel Collab.)
GANZ	96	PL B389 4	+Baer, Balanda+	(GSI, HEID, FRAN, JAGL, MPIH)
GUENTHER	96	PR D54 3641	+Hellmig, Heusser, Hirsch+	(MPIH, SASSO)
KAMEL	96	PL B368 291		(SHAMS)
MITSUI	96	EPL 33 111	+Maki, Asai, Ishisaki+	(TOKY)
YOUDIN	96	PRL 77 2170	+Krause, Jagannathan, Hunter+	(AMHT, WASH)
ALTMANN	95	ZPHY C68 221	+Declais, v. Feilitzsch+	(MUNT, LAPP, CPPM)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
BASSOMPIE...	95	PL B355 584	Bassompierre, Bologna+	(LAPP, LCGT, LYON)
MAENO	95	PL B351 574	+Fujikawa, Kataoka, Nishihara+	(TOKY)
RAFFELT	95	PR D51 1495	+Weiss	(MPIM, MPIA)
SKALSEY	95	PR D51 6292	+Conti	(MICH)
TSUNODA	95	EPL 30 273	+Nakamura, Orito, Minowa	(TOKY)
ADACHI	94	PR A49 3201	+Chiba, Hirose, Nagayama+	(TMU)
ALTHERR	94	ASP 2 175	+Petitgirard, del Rio Gaztelurrutia	(CERN, LAPP, DFAB)
AMSLER	94B	PL B333 271	+Armstrong, Ould-Saada+	(Crystal Barrel Collab.)
ASAI	94	PL B323 90	+Shigekuni, Sanuki, Orito	(TOKY)
MEIJERDREES	94	PR D49 4937	Meijer Drees, Waltham+	(BRCO, OREG, TRIU)
NI	94	Physica B194 153	+Chui, Pan, Cheng	(NTHU)
VO	94	PR C49 1551	+Kelly, Wohn, Hill+	(ISU, LBL, LLNL, UCD)
ATIYA	93	PRL 70 2521	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
Also	93C	PRL 71 305 (erratum)	Atiya, Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
ATIYA	93B	PR D48 R1	+Chiang, Frank, Haggerty, Ito+	(BNL 787 Collab.)
BASSOMPIE...	93	EPL 22 239	Bassompierre, Bologna+	(LAPP, TORI, LYON)
BECK	93	PRL 70 2853	+Bensch, Bockholt, Heusser, Hirsch+	(MPIH, KIAE, SASSO)

CAMERON 93 PR D47 3707 +Cantatore, Melissinos+ (ROCH, BNL, FNAL, TRST)
CHUI 93 PRL 71 3247 +Ni (NTHU)
MINOWA 93 PRL 71 4120 +Inoue, Asanuma, Imamura (TOKY)
NG 93 PR D48 2941 (AST)
TANAKA 93 PR D48 5412 +Ejiri (OSAK)
ALLIEGRO 92 PRL 68 278 +Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
ATIYA 92 PRL 69 733 +Chiang, Frank, Haggerty, Ito+ (BNL, LANL, PRIN, TRIU)
BERNATOW... 92 PRL 69 2341 Bernatowicz, Brannon, Brazzle, Cowsik+ (WUSL, TATA)
BLUEMLEIN 92 IJMP A7 3835 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
HALLIN 92 PR D45 3955 +Calaprice, McPherson, Saettler (PRIN)
HENDERSON 92C PRL 69 1733 +Asoka-Kumar, Greenberg, Lynn+ (YALE, BNL)
HICKS 92 PL B276 423 +Alburger (OHIO, BNL)
LAZARUS 92 PRL 69 2333 +Smith, Cameron, Melissinos+ (BNL, ROCH, FNAL)
MEIJERDREES 92 PRL 68 3845 Meijer Drees, Waltham+ (SINDRUM I Collab.)
PAN 92 MPL 7 1287 +Ni, Chen (NTHU)
RUOSO 92 ZPHY C56 505 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
SKALSEY 92 PRL 68 456 +Kolata (MICH, NDAM)
WANG 92 MPL A7 1497 (ILL)
WANG 92C PL B291 97 (ILL)
WU 92 PRL 69 1729 +Asoka-Kumar, Greenberg, Henderson+(BNL, YALE, CUNY)
AKOPYAN 91 PL B272 443 +Atoyan, Gninenko, Sukhov (INRM)
ASAI 91 PRL 66 2440 +Orito, Yoshimura, Haga (ICEPP)
BERSHADY 91 PRL 66 1398 +Ressell, Turner (CHIC, FNAL, EFI)
BLUEMLEIN 91 ZPHY C51 341 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
BOBRAKOV 91 JETPL 53 294 +Borisov, Lasakov, Serebrov, Tal'daev, Trofimova (PNPI)
Translated from ZETFP 53 283.
BROSS 91 PRL 67 2942 +Crisler, Pordes, Volk, Errede, Wrbanek (FNAL, ILL)
KIM 91C PRL 67 3465 (SEOUL)
RAFFELT 91B PRL 67 2605 +Seckel (MPIM, BART)
RESSELL 91 PR D44 3001 (CHIC, FNAL)
TRZASKA 91 PL B269 54 +Dejbakhsh, Dutta, Li, Cormier (TAMU)
TSERTOS 91 PL B266 259 +Kienle, Judge, Schreckenbach (ILLG, GSI)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
WIDMANN 91 ZPHY A340 209 +Bauer, Connell, Maier, Major+ (STUT, GSI, STUTM)
WINELAND 91 PRL 67 1735 +Bollinger, Heinzen, Itano, Raizen (NBSB)
ALBRECHT 90E PL B246 278 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
ASANUMA 90 PL B237 588 +Minowa, Tsukamoto, Orito, Tsunoda (TOKY)
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
BAUER 90 NIM B50 300 +Briggmann, Carstanjen, Connell+ (STUT, VILL, GSI)
BURROWS 90 PR D42 3297 +Ressell, Turner (ARIZ, CHIC, FNAL)
DEBOER 90 JPG 16 L1 de Boer, Lehmann, Steyaert (LOUV)
ENGEL 90 PRL 65 960 +Seckel, Hayes (BART, LANL)
GNINENKO 90 PL B237 287 +Klubakov, Poblaguev, Postoev (INRM)
GUO 90 PR D41 2924 +Kaplan, Alde+ (NIU, LANL, FNAL, CASE, TEXA)
HAGMANN 90 PR D42 1297 +Sikivie, Sullivan, Tanner (FLOR)
JUDGE 90 PRL 65 972 +Krusche, Schreckenbach, Tsertos, Kienle (ILLG, GSI)
RAFFELT 90C PRPL 198 1 (MPIM)
RAFFELT 90D PR D41 1324 (MPIM)
RITTER 90 PR D42 977 +Goldblum, Ni, Gillies, Speake (VIRG)
SEMERTZIDIS 90 PRL 64 2988 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
TSUCHIAKI 90 PL B236 81 +Orito, Yoshida, Minowa (ICEPP)
TURNER 90 PRPL 197 67 (FNAL)
BARABASH 89 PL B223 273 +Kuzminov, Lobashev, Novikov+ (ITEP, INRM)
BINI 89 PL B221 99 +Fazzini, Giannatiempo, Poggi, Sona+(FIRZ, CERN, AARH)
BURROWS 89 PR D39 1020 +Turner, Brinkmann (ARIZ, CHIC, FNAL, BOCH)
Also 88 PRL 60 1797 Turner (FNAL, EFI)
DEBOER 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
ERICSON 89 PL B219 507 +Mathiot (CERN, IPN)
FAISSNER 89 ZPHY C44 557 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, PSI)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
FOX 89 PR C39 288 +Kemper, Cottle, Zingarelli (FSU)
MAYLE 89 PL B219 515 +Wilson, Ellis+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
Also 88 PL B203 188 Mayle, Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA 89 PRL 62 1091 +Orito, Tsuchiaki, Tsukamoto (ICEPP)
ORITO 89 PRL 63 597 +Yoshimura, Haga, Minowa, Tsuchiaki (ICEPP)
PERKINS 89 PRL 62 2638 (OXF)
TSERTOS 89 PR D40 1397 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANBIBBER 89 PR D39 2089 Van Bibber, McIntyre, Morris, Raffelt (LLL, TAMU, LBL)
WUENSCH 89 PR D40 3153 +De Panfilis-Wuensch, Semertzidis+ (ROCH, BNL, FNAL)
Also 87 PRL 59 839 De Panfilis, Melissinos, Moskowitz+ (ROCH, BNL, FNAL)
ALSTON-... 88 PRL 60 1928 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM)
AVIGNONE 88 PR D37 618 +Baktash, Barker, Calaprice+(PRIN, SCUC, ORNL, WASH)
BJORKEN 88 PR D38 3375 +Ecklund, Nelson, Abashian+ (FNAL, SLAC, VPI)
BLINOV 88 SJNP 47 563 +Bondar, Bukin, Vorobyev, Groshev+ (NOVO)
Translated from YAF 47 889.
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
CHANDA 88 PR D37 2714 +Nieves, Pal (UMD, UPR, MASA)
CHOI 88 PR D37 3225 +Kim, Kim, Lam (JHU)
CONNELL 88 PRL 60 2242 +Fearick, Hoernle, Sideras-Haddad, Sellschop (WITW)
DATAR 88 PR C37 250 +Fortier, Gales, Hourani+ (IPN)
DEBOER 88 PRL 61 1274 de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2644 erratum de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2638 Perkins (OXF)
Also 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
DEBOER 88C JPG 14 L131 de Boer, Deutsch, Lehmann, Prieels, Steyaert (LOUV)
DOEHNER 88 PR D38 2722 +Last, Arnold, Freedman, Dubbers (HEIDP, ANL, ILLG)
DOI 88 PR D37 2575 +Kotani, Takasugi (OSAK)
EL-NADI 88 PRL 61 1271 +Badawy (CAIR)
FAISSNER 88 ZPHY C37 231 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, SIN)
HATSUDA 88B PL B203 469 +Yoshimura (KEK)
LORENZ 88 PL B214 10 +Mageras, Stiegler, Huszar (MPIM, PSI)
MAYLE 88 PL B203 188 +Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO 88 PR D37 1131 +Ahmad, Britton, Bryman, Clifford+ (TRIU, CNRC)
RAFFELT 88 PRL 60 1793 +Seckel (UCB, LLL, UCSC)
RAFFELT 88B PR D37 549 +Dearborn (UCB, LLL)
SAVAGE 88 PR D37 1134 +Filippone, Mitchell (CIT)
TSERTOS 88 PL B207 273 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
TSERTOS 88B ZPHY A331 103 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANKLINKEN 88 PL B205 223 van Klinken, Meiring, de Boer, Schaafsma+ (GRON, GSI)
VANKLINKEN 88B PRL 60 2442 van Klinken (GRON)
VONWIMMER...88 PRL 60 2443 von Wimmersperg (BNL)
VOROBYOV 88 PL B208 146 +Gitarts (NOVO)
AVIGNONE 87 AIP Conf. 1987 +Brodzinski, Miley, Reeves (SCUC, PNL)
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CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ELLIOTT 87 PRL 59 1649 +Hahn, Moe (UCI)
FISHER 87 PL B192 460 +Boehm, Bovet, Egger+ (CIT, NEUC, SIN)
FRIEMAN 87 PR D36 2201 +Dimopoulos, Turner (SLAC, STAN, FNAL, EFI)
GOLDMAN 87 PR D36 1543 +Hallin, Hoffman+ (LANL, CHIC, STAN, TEMP)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
MAIER 87 ZPHY A326 527 +Bauer, Briggmann, Carstanjen+ (STUT, GSI)
MILLS 87 PR D36 707 +Levy (BELL)
RAFFELT 87 PR D36 2211 +Dearborn (LLL, UCB)
RIORDAN 87 PRL 59 755 +Krasny, Lang, Barbaro, Bodek+ (ROCH, CIT+)
TURNER 87 PRL 59 2489 (FNAL, EFI)
VANBIBBER 87 PRL 59 759 Van Bibber, Dagdeviren, Koonin+(LLL, CIT, MIT, STAN)
VONWIMMER...87 PRL 59 266 von Wimmersperg, Connell, Hoernle, Sideras-Haddad(WITW)
ALBRECHT 86D PL B179 403 +Binder, Boeckmann+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BOWCOCK 86 PRL 56 2676 +Giles, Hassard, Kinoshita+ (CLEO Collab.)
BROWN 86 PRL 57 2101 + (FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN 86B PRL 57 2787 +Clifford (TRIU)
DAVIER 86 PL B180 295 +Jeanjean, Nguyen Ngoc (LALO)
DEARBORN 86 PRL 56 26 +Schramm, Steigman (LLL, CHIC, FNAL, BART)
EICHLER 86 PL B175 101 +Felawka, Kraus, Niebuhr+ (SINDRUM Collab.)
HALLIN 86 PRL 57 2105 +Calparice, Dunford, McDonald (PRIN)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
KETOV 86 JETPL 44 146 +Klimov, Nikolaev, Mikaelyan+ (KIAE)
Translated from ZETFP 44 114.
KOCH 86 NC 96A 182 +Schult (JULI)
KONAKA 86 PRL 57 659 +Imai, Kobayashi, Masaike, Miyake+ (KYOT, KEK)
MAGERAS 86 PRL 56 2672 +Franzini, Tuts, Youssef+ (MPIM, COLU, STON)
MAIANI 86 PL B175 359 +Petronzio, Zavattini (CERN)
PECCEI 86 PL B172 435 +Wu, Yanagida (DESY)
RAFFELT 86 PR D33 897 (MPIM)
RAFFELT 86B PL 166B 402 (MPIM)
SAVAGE 86B PRL 57 178 +McKeown, Filippone, Mitchell (CIT)
AMALDI 85 PL 153B 444 +Carboni, Jonson, Thun (CERN)
ANANEV 85 SJNP 41 585 +Kalinina, Lushchikov, Olshevskii+ (JINR)
Translated from YAF 41 912.
BALTRUSAIT... 85 PRL 55 1842 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BERGSMA 85 PL 157B 458 +Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
KAPLAN 85 NP B260 215 (HARV)
IWAMOTO 84 PRL 53 1198 (UCSB, WUSL)
YAMAZAKI 84 PRL 52 1089 +Ishikawa, Taniguchi, Yamanaka+ (INUS, KEK)
ABBOTT 83 PL 120B 133 +Sikivie (BRAN, FLOR)
ALAM 83 PR D27 1665 + (VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI 83 PL 123B 349 +Dahme (CERN, MUNI)
CAVAIGNAC 83 PL 121B 193 +Hoummada, Koang, Ost+ (ISNG, LAPP)
DICUS 83 PR D28 1778 +Teplitz (TEXA, UMD)
DINE 83 PL 120B 137 +Fischler (IAS, PENN)
ELLIS 83B NP B223 252 +Olive (CERN)
FAISSNER 83 PR D28 1198 +Heinrigs, Preussger, Samm (AACH)
FAISSNER 83B PR D28 1787 +Frenzel, Heinrigs, Preussger+ (AACH3)
FRANK 83B PR D28 1790 + (LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
NICZYPORUK 83 ZPHY C17 197 +Jakubowski, Zeludziewicz+ (LENA Collab.)
PRESKILL 83 PL 120B 127 +Wise, Wilczek (HARV, UCSBT)
SIKIVIE 83 PRL 51 1415 (FLOR)
Also 84 PRL 52 695 erratum Sikivie (FLOR)
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
ALEKSEEV 82B JETPL 36 116 +Kalinina, Kruglov, Kulikov+ (MOSU, JINR)
Translated from ZETFP 36 94.
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO 82 PL 116B 247 +Branco (LISB)
DATAR 82 PL 114B 63 +Baba, Betigeri, Singh (BHAB)
EDWARDS 82 PRL 48 903 +Partridge, Peck, Porter+ (Crystal Ball Collab.)
FETSCHER 82 JPG 8 L147 (ETH)
FUKUGITA 82 PRL 48 1522 +Watamura, Yoshimura (KEK)
FUKUGITA 82B PR D26 1840 +Watamura, Yoshimura (KEK)
LEHMANN 82 PL 115B 270 +Lesquoy, Muller, Zylberajch (SACL)
RAFFELT 82 PL 119B 323 +Stodolsky (MPIM)
SIVERTZ 82 PR D26 717 +Lee-Franzini, Horstkotte+ (CUSB Collab.)
VERGADOS 82 PL 109B 96 (CERN)
ZEHNDER 82 PL 110B 419 +Gabathuler, Vuilleumier (ETH, SIN, CIT)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO 81 PL 106B 91 +Mukhopadhyay (SIN)
FAISSNER 81 ZPHY C10 95 +Frenzel, Grimm, Hansl, Hoffman+ (AACH3)
FAISSNER 81B PL 103B 234 +Frenzel, Heinrigs, Preussger+ (AACH3)
KIM 81 PL 105B 55 +Stamm (AACH3)
VUILLEUMIER 81 PL 101B 341 +Boehm, Hahn, Kwon+ (CIT, MUNI)
ZEHNDER 81 PL 104B 494 (ETH)
FAISSNER 80 PL 96B 201 +Frenzel, Heinrigs, Preussger, Samm+ (AACH3)
JACQUES 80 PR D21 1206 +Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
SOUKAS 80 PRL 44 564 +Wanderer, Weng+ (BNL, HARV, ORNL, PENN)
BECHIS 79 PRL 42 1511 +Dombeck+ (UMD, COLU, AFRR)
CALAPRICE 79 PR D20 2708 +Dunford, Kouzes, Miller+ (PRIN)
COTEUS 79 PRL 42 1438 +Diesburg, Fine, Lee, Sokolsky+ (COLU, ILL, BNL)
DISHAW 79 PL 85B 142 +Diamant-Berger, Faessler, Liu+ (SLAC, CIT)
ZHITNITSKII 79 SJNP 29 517 +Skovpen (NOVO)
Translated from YAF 29 1001.
ALIBRAN 78 PL 74B 134 +Armenise, Arnold, Bartley (Gargamelle Collab.)
ASRATYAN 78B PL 79B 497 +Epstein, Fakhrutdinov+ (ITEP, SERP)
BELLOTTI 78 PL 76B 223 +Florini, Zanotti (MILA)
BOSETTI 78B PL 74B 143 +Deden, Deutschmann, Fritze+ (BEBC Collab.)
DICUS 78C PR D18 1829 +Kolb, Teplitz, Wagoner (TEXA, VPI, STAN)
DONNELLY 78 PR D18 1607 +Freedman, Lytel, Peccei, Schwartz (STAN)
Also 76 PRL 37 315 Reines, Gurr, Sobel (UCI)
Also 74 PRL 33 179 Gurr, Reines, Sobel (UCI)
HANSL 78D PL 74B 139 +Holder, Knobloch, May, Paar+ (CDHS Collab.)
MICELMAC... 78 LNC 21 441 Micelmacher, Pontecorvo (JINR)
MIKAELIAN 78 PR D18 3605 (FNAL, NWES)
SATO 78 PTP 60 1942 (KYOT)
VYSOTSKII 78 JETPL 27 502 +Zeldovich, Khlopov, Chechetkin (ASCI)
Translated from ZETFP 27 533.
YANG 78 PRL 41 523 (MASA)
PECCEI 77 PR D16 1791 +Quinn (STAN, SLAC)
Also 77B PRL 38 1440 Peccei, Quinn (STAN, SLAC)
REINES 76 PRL 37 315 +Gurr, Sobel (UCI)
GURR 74 PRL 33 179 +Reines, Sobel (UCI)
ANAND 53 PRSL A22 183

OTHER RELATED PAPERS

SREDNICKI 85 NP B260 689 (UCSB)
BARDEEN 78 PL 74B 229 +Tye (FNAL)

LEPTONS

Notes in the Lepton Listings

LEPTONS

e

$J = \frac{1}{2}$

e MASS

The mass is known much more precisely in u (atomic mass units) than in MeV (see the footnote). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.51099907±0.00000015	[1] FARNHAM 95	CNTR	Penning
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.51099906±0.00000015	[2] COHEN 87	RVUE	1986 CODATA value
0.5110034 ±0.0000014	COHEN 73	RVUE	1973 CODATA value

[1] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{+6}$ ion. The result is $m_e = 0.0005485799111(12)$ u, where the figure in parenthesis is the 1σ uncertainty in the last digit. The uncertainty after conversion to MeV is dominated by the uncertainty in the electron charge.

[2] COHEN 87 (1986 CODATA) value in atomic mass units is 0.000548579903(13). See footnote on FARNHAM 95.

$(m_{e^+} - m_{e^-}) / m_{\mathrm{average}}$

A test of *CPT* invariance.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<4 × 10^{-8}	90	CHU 84	CNTR	Positronium spectroscopy

$|q_{e^+} + q_{e^-}|/e$

A test of *CPT* invariance. See also similar tests involving the proton.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<4 × 10^{-8}	[3] HUGHES 92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<2 × 10^{-18}	[4] SCHAEFER 95	THEO	Vacuum polarization
<1 × 10^{-18}	[5] MUELLER 92	THEO	Vacuum polarization

[3] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.

[4] SCHAEFER 95 removes model dependency of MUELLER 92.

[5] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

e MAGNETIC MOMENT ANOMALY

$\mu_e/\mu_B - 1 = (g-2)/2$

For the most accurate theoretical calculation, see KINOSHITA 81.

Some older results have been omitted.

VALUE (units 10^{-6})	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1159.652193 ±0.000010	[6] COHEN 87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1159.6521884±0.0000043	VANDYCK 87	MRS	−	Single electron
1159.6521879±0.0000043	VANDYCK 87	MRS	+	Single positron
1159.652200 ±0.000040	VANDYCK 86	MRS	−	Single electron
1159.652222 ±0.000050	SCHWINBERG 81	MRS	+	Single positron

[6] The COHEN 87 value assumes the $g/2$ values for e^+ and e^- are equal, as required by *CPT*.

$(g_{e^+} - g_{e^-}) / g_{\mathrm{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-12})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
− 0.5± 2.1		[7] VANDYCK 87	MRS	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 12	95	[8] VASSERMAN 87	CNTR	Assumes $m_{e^+} = m_{e^-}$
22 ±64		SCHWINBERG 81	MRS	Penning trap

[7] VANDYCK 87 measured $(g_-/g_+)-1$ and we converted it.

[8] VASSERMAN 87 measured $(g_+ - g_-)/(g-2)$. We multiplied by $(g-2)/g = 1.2 \times 10^{-3}$.

e ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-26} *e*cm)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18± 0.12±0.10		[9] COMMINS 94	MRS	^{205}Tl beams
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 0.27± 0.83		[9] ABDULLAH 90	MRS	^{205}Tl beams
− 14 ± 24		CHO 89	NMR	Tl F molecules
− 1.5 ± 5.5 ±1.5		MURTHY 89		Cesium, no *B* field
− 50 ±110		LAMOREAUX 87	NMR	^{199}Hg
190 ±340	90	SANDARS 75	MRS	Thallium
70 ±220	90	PLAYER 70	MRS	Xenon
< 300	90	WEISSKOPF 68	MRS	Cesium

[9] ABDULLAH 90 and COMMINS 94 use the relativistic enhancement of a valence electron's electric dipole moment in a high-Z atom.

e MEAN LIFE / BRANCHING FRACTION

A test of charge conservation. See the "Note on Testing Charge Conservation and the Pauli Exclusion Principle" following this section in our 1992 edition (Physical Review **D45**, 1 June, Part II (1992), p. VI.10). We use the best "disappearance" limit for the Summary Tables. The best limit for the specific channel $e^- \to \nu\gamma$ is much better.

Note that we use the mean life rather than what is often reported, the half life.

VALUE (yr)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>4.3 × 10^{23}	68	AHARONOV 95B	CNTR	Ge K-shell disappearance
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>3.7 × 10^{25}	68	AHARONOV 95B	CNTR	$e^- \to \nu\gamma$
>2.35 × 10^{25}	68	BALYSH 93	CNTR	$e^- \to \nu\gamma$, ^{76}Ge detector
>2.7 × 10^{23}	68	REUSSER 91	CNTR	Ge K-shell disappearance
>1.5 × 10^{25}	68	AVIGNONE 86	CNTR	$e^- \to \nu\gamma$
>1 × 10^{39}		[10] ORITO 85	ASTR	Astrophysical argument
>3 × 10^{23}	68	BELLOTTI 83B	CNTR	$e^- \to \nu\gamma$
>2 × 10^{22}	68	BELLOTTI 83B	CNTR	Ge K-shell disappearance

[10] ORITO 85 assumes that electromagnetic forces extend out to large enough distances and that the age of our galaxy is 10^{10} years.

e REFERENCES

AHARONOV	95B	PR D52 3785	+Avignon, Brodzinski, Collar+	(SCUC, PNL, ZAGR, TELA)
Also	95	PL B353 168	Aharonov, Avignone+	(SCUC, PNL, ZAGR, TELA)
FARNHAM	95	PRL 75 3598	+Van Dyck, Schwinberg	(WASH)
SCHAEFER	95	PR A51 838	A. Schaefer, J. Reinhardt	(FRAN)
COMMINS	94	PR A50 2960	E.D. Commins, S.B. Ross, D. DeMille, B.C. Regan	
BALYSH	93	PL B298 278	+Beck, Belyaev, Bensch+	(KIAE, MPIH, SASSO)
HUGHES	92	PRL 69 578	+Deutch	(LANL, AARH)
MUELLER	92	PRL 69 3432	+Thoma	(DUKE)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
REUSSER	91	PL B255 143	+Treichel, Boehm, Broggini+	(NEUC, CIT, PSI)
ABDULLAH	90	PRL 65 2347	+Carlberg, Commins, Gould, Ross	(LBL, UCB)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
MURTHY	89	PRL 63 965	+Krause, Li, Hunter	(AMHT)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
LAMOREAUX	87	PRL 59 2275	+Jacobs, Heckel, Raab, Fortson	(WASH)
VANDYCK	87	PRL 59 26	Van Dyck, Schwinberg, Dehmelt	(WASH)
VASSERMAN	87	PL B198 302	+Vorobyov, Gluskin+	(NOVO)
Also	87B	PL B187 172	Vasserman, Vorobyov, Gluskin+	(NOVO)
AVIGNONE	86	PR D34 97	+Brodzinski, Hensley, Miley, Reeves+	(PNL, SCUC)
VANDYCK	86	PR D34 722	Van Dyck, Schwinberg, Dehmelt	(WASH)
ORITO	85	PRL 54 2457	+Yoshimura	(TOKY, KEK)
CHU	84	PRL 52 1689	+Mills, Hall	(BELL, NBS, COLO)
BELLOTTI	83B	PL 124B 435	+Corti, Fiorini, Liguori, Pullia+	(MILA)
KINOSHITA	81	PRL 47 1573	+Lindquist	(CORN)
SCHWINBERG	81	PRL 47 1679	+Van Dyck, Dehmelt	(WASH)
SANDARS	75	PR A11 473	+Sternheimer	(OXF, BNL)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
PLAYER	70	JPB 3 1620	+Sandars	(OXF)
WEISSKOPF	68	PRL 21 1645	+Carrico, Gould, Lipworth+	(BRAN)

μ

$J = \frac{1}{2}$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

Where m_μ/m_e was measured, we have used the 1986 CODATA value for $m_e = 0.51099906 \pm 0.00000015$ MeV.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.658389±0.000034	[1] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.65841 ±0.00033	[2] BELTRAMI	86	SPEC	−	Muonic atoms
105.658432±0.000064	[3] KLEMPT	82	CNTR	+	Incl. in MARIAM 82
105.658386±0.000044	[4] MARIAM	82	CNTR	+	
105.65856 ±0.00015	[5] CASPERSON	77	CNTR	+	
105.65836 ±0.00026	[6] CROWE	72	CNTR		
105.65865 ±0.00044	[7] CRANE	71	CNTR		

[1] The mass is known more precisely in u: $m = 0.113428913 \pm 0.000000017$ u. COHEN 87 makes use of the other entries below.

[2] BELTRAMI 86 gives $m_\mu/m_e = 206.76830(64)$.

[3] KLEMPT 82 gives $m_\mu/m_e = 206.76835(11)$.

[4] MARIAM 82 gives $m_\mu/m_e = 206.768259(62)$.

[5] CASPERSON 77 gives $m_\mu/m_e = 206.76859(29)$.

[6] CROWE 72 gives $m_\mu/m_e = 206.7682(5)$.

[7] CRANE 71 gives $m_\mu/m_e = 206.76878(85)$.

μ MEAN LIFE τ

Measurements with an error > 0.001×10^{-6} s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/μ^-

$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

VALUE	*DOCUMENT ID*
$(2\pm8) \times 10^{-5}$ OUR EVALUATION	

μ MAGNETIC MOMENT ANOMALY

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

For reviews of theory and experiments, see HUGHES 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-8})	*DOCUMENT ID*	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-19} ecm)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.7±3.4	[9] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[9] This is the combination of the two BAILEY 78 results given below.

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass. Measurements with an error > 0.00001 have been omitted.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.18334547±0.00000047	[10] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

[10] COHEN 87 (1986 CODATA) value was fitted using their own selection of the following data. Because their value is from a multiparameter fit, correlations with other quantities may be important and one cannot arrive at this result by any average of these data alone.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$		≈ 100%		
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$		[a] (1.4 ± 0.4) %		
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$		[b] $(3.4\pm0.4) \times 10^{-5}$		
	Lepton Family number (*LF*) violating modes				
Γ_4	$e^-\nu_e\overline{\nu}_\mu$	*LF*	[c] < 1.2	%	90%
Γ_5	$e^-\gamma$	*LF*	< 4.9	$\times 10^{-11}$	90%
Γ_6	$e^-e^+e^-$	*LF*	< 1.0	$\times 10^{-12}$	90%
Γ_7	$e^-2\gamma$	*LF*	< 7.2	$\times 10^{-11}$	90%

[a] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] A test of additive vs. multiplicative lepton family number conservation.

μ^- BRANCHING RATIOS

$\Gamma(e^-\overline{\nu}_e\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^-\overline{\nu}_e\nu_\mu e^+e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.4±0.2±0.3	7443	[11] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[12] CRITTENDEN	61	HLBC	+	$E(e^+e^-)$>10 MeV
2	1	[13] GUREVICH	60	EMUL	+	
1.5±1.0	3	[14] LEE	59	HBC	+	

[11] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[14] In the three LEE 59 events, the sum of energies $E(e^+) + E(e^-) + E(e^+)$ was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\text{total}}$ Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 0.012	90	[15] FREEDMAN	93	CNTR	+	ν oscillation search
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.018	90	KRAKAUER	91B	CALO	+	
< 0.05	90	[16] BERGSMA	83	CALO		$\overline{\nu}_\mu e \rightarrow \mu^-\overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
-0.001 ± 0.061		WILLIS	80	CNTR	+	
$0.13\ \pm0.15$		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[15] FREEDMAN 93 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton family number violation.

[16] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \rightarrow \mu^-\overline{\nu}_e)/\sigma(\nu_\mu e^- \rightarrow \mu^-\nu_e)$, which is essentially equivalent to $\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\text{total}}$ for small values like that quoted.

$\Gamma(e^-\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^-e^+e^-)/\Gamma_{\text{total}}$ Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[17] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[17] BERTL	85	SPEC	+	SINDRUM
<160	90	[17] BERTL	84	SPEC	+	SINDRUM
<130	90	[17] BOLTON	84	CNTR		LAMPF

[17] These experiments assume a constant matrix element.

$\Gamma(e^-2\gamma)/\Gamma_{\text{total}}$ Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[18] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[19] BOWMAN	78	CNTR		DEPOMMIER 77 data

[18] AZUELOS 83 uses the phase space distribution of BOWMAN 78.

[19] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \rightarrow e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^-\,{}^{32}\text{S} \rightarrow e^-\,{}^{32}\text{S})$ / $\sigma(\mu^-\,{}^{32}\text{S} \rightarrow \nu_\mu\,{}^{32}\text{P}^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-11}	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4 × 10^{-10}	90	BADERT...	77	STRC	SIN

$\sigma(\mu^-\text{Cu} \rightarrow e^-\text{Cu})$ / $\sigma(\mu^-\text{Cu} \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.6 × 10^{-8}	90	BRYMAN	72	SPEC

$\sigma(\mu^-\text{Ti} \rightarrow e^-\text{Ti})$ / $\sigma(\mu^-\text{Ti} \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.3 × 10^{-12}	90	[20] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.6 × 10^{-12}	90	AHMAD	88	TPC	TRIUMF
<1.6 × 10^{-11}	90	BRYMAN	85	TPC	TRIUMF

[20] DOHMEN 93 assumes $\mu^- \rightarrow e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^-\text{Pb} \rightarrow e^-\text{Pb})$ / $\sigma(\mu^-\text{Pb} \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.6 × 10^{-11}	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.9 × 10^{-10}	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \rightarrow e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^-\,{}^{32}\text{S} \rightarrow e^+\,{}^{32}\text{Si}^*)$ / $\sigma(\mu^-\,{}^{32}\text{S} \rightarrow \nu_\mu\,{}^{32}\text{P}^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9 × 10^{-10}	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5 × 10^{-9}	90	BADERT...	78	STRC	SIN

$\sigma(\mu^-\,{}^{127}\text{I} \rightarrow e^+\,{}^{127}\text{Sb}^*)$ / $\sigma(\mu^-\,{}^{127}\text{I} \rightarrow \text{anything})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3 × 10^{-10}	90	[21] ABELA	80	CNTR	Radiochemical tech.

[21] ABELA 80 is upper limit for μ^-e^+ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^-\text{Cu} \rightarrow e^+\text{Co})$ / $\sigma(\mu^-\text{Cu} \rightarrow \nu_\mu\text{Ni})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6 × 10^{-8}	90	BRYMAN	72	SPEC
<2.2 × 10^{-7}	90	CONFORTO	62	OSPK

$\sigma(\mu^-\text{Ti} \rightarrow e^+\text{Ca})$ / $\sigma(\mu^-\text{Ti} \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.9 × 10^{-11}	90	[22] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.3 × 10^{-12}	90	[23] DOHMEN	93	SPEC	SINDRUM II
<1.7 × 10^{-10}	90	[24] AHMAD	88	TPC	TRIUMF

[22] This DOHMEN 93 limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).

[23] This DOHMEN 93 limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.

[24] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C\ /\ G_F$

The effective Lagrangian for the $\mu^+e^- \rightarrow \mu^-e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2}\, G_C\, [\overline{\psi}_\mu\gamma_\lambda\,(1-\gamma_5)\,\psi_e]\,[\overline{\psi}_\mu\gamma_\lambda\,(1-\gamma_5)\,\psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C/G_F, where G_F is the Fermi coupling constant.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.018	90	0	[25] ABELA	96	SPEC	+	μ^+ at 24 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.14	90	1	[26] GORDEEV	97	SPEC	+	JINR phasotron
< 6.9	90		NI	93	CBOX		LAMPF
< 0.16	90		MATTHIAS	91	SPEC		LAMPF
< 0.29	90		HUBER	90B	CNTR		TRIUMF
<20	95		BEER	86	CNTR		TRIUMF
<42	95		MARSHALL	82	CNTR		

[25] ABELA 96 quote both probability $P_{M\overline{M}} < 8 \times 10^{-9}$ at 90% CL and $R_g = G_C/G_F$.

[26] GORDEEV 97 quote limits on both $f{=}G_{MM}/GF$ and the probability $W_{MM} < 4.7 \times 10^{-7}$ (90%CL).

MUON DECAY PARAMETERS

Revised October 1997 by W. Fetscher and H.-J. Gerber (ETH Zürich).

Introduction: All measurements in direct muon decay, $\mu^- \rightarrow e^- + 2$ neutrals, and its inverse, $\nu_\mu + e^- \rightarrow \mu^- + \text{neutral}$, are successfully described by the "V-A interaction", which is a particular case of a local, derivative-free, lepton-number-conserving, four fermion interaction [1]. As shown below, within this framework, the Standard Model assumptions, such as the V-A form and the nature of the neutrals (ν_μ and $\bar{\nu}_e$), and hence the doublet assignments $(\nu_e\ e^-)_L$ and $(\nu_\mu\ \mu^-)_L$, have been determined from experiments [2,3]. All considerations on muon decay are valid for the leptonic tau decays $\tau \rightarrow \ell + \nu_\tau + \bar{\nu}_e$ with the replacements $m_\mu \rightarrow m_\tau$, $m_e \rightarrow m_\ell$.

Parameters: The differential decay probability to obtain an $e^\pm$ with (reduced) energy between x and $x + dx$, emitted in the direction $\hat{z}$ at an angle between ϑ and $\vartheta + d\vartheta$ with respect to the muon polarization vector $\vec{P}_\mu$, and with its spin pointing in the arbitrary direction $\hat{\zeta}$, neglecting radiative corrections, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\ d\cos\vartheta} = &\frac{m_\mu}{4\pi^3}\, W_{e\mu}^4\, G_F^2\, \sqrt{x^2 - x_0^2} \\ &\times \left(F_{IS}(x) \pm P_\mu \cos\vartheta\ F_{AS}(x)\right) \\ &\times \left[1 + \vec{P}_e(x,\vartheta)\cdot\hat{\zeta}\right]\ . \qquad (1)\end{aligned}$$

Here, $W_{e\mu} = \max(E_e) = (m_\mu^2 + m_e^2)/2m_\mu$ is the maximum $e^\pm$ energy, $x = E_e/W_{e\mu}$ is the reduced energy, $x_0 = m_e/W_{e\mu} = 9.67 \times 10^{-3}$, and $P_\mu = |\vec{P}_\mu|$ is the degree of muon polarization. $\hat{\zeta}$ is the direction in which a perfect polarization-sensitive electron detector is most sensitive. The isotropic part of the spectrum, $F_{IS}(x)$, the anisotropic part $F_{AS}(x)$ and the electron polarization, $\vec{P}_e(x,\vartheta)$, may be parametrized by the Michel parameters [1,4] ρ, η, ξ, δ, *etc.* These are bilinear combinations of the coupling constants $g_{\epsilon\mu}^\gamma$, which occur in the matrix element (given below).

If the masses of the neutrinos as well as x_0^2 are neglected, the energy and angular distribution of the electron in the rest frame of a muon ($\mu^\pm$) measured by a polarization insensitive detector, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\ d\cos\vartheta} \sim x^2\cdot &\left\{3(1-x) + \frac{2\rho}{3}(4x-3) + 3\eta\ x_0(1-x)/x\right. \\ &\left.\pm\ P_\mu\cdot\xi\cdot\cos\vartheta\left[1 - x + \frac{2\delta}{3}(4x-3)\right]\right\}\ .\end{aligned}$$

Here, ϑ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. For the Standard Model coupling, we obtain $\rho = \xi\delta = 3/4$, $\xi = 1$, $\eta = 0$ and the differential decay rate is

$$\frac{d^2\Gamma}{dx\ d\cos\vartheta} = \frac{G_F^2 m_\mu^5}{192\pi^3}\ [3 - 2x \pm P_\mu\cos\vartheta(2x-1)]\ x^2\ \ .$$

The coefficient in front of the square bracket is the total decay rate.

If only the neutrino masses are neglected, and if the $e^\pm$ polarization is detected, then the functions in Eq. (1) become

$$\begin{aligned}&F_{IS}(x) = x(1-x) + \tfrac{2}{9}\ \rho(4x^2 - 3x - x_0^2) + \eta\cdot x_0(1-x) \\ &F_{AS}(x) = \tfrac{1}{3}\xi\ \sqrt{x^2 - x_0^2} \\ &\qquad\qquad \times\left[1 - x + \tfrac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1-x_0^2} - 1\right)\right)\right] \\ &\vec{P}_e(x,\vartheta) = P_{T_1}\ \hat{x} + P_{T_2}\hat{y} + P_L\ \hat{z}\ .\end{aligned}$$

Here $\hat{x}$, $\hat{y}$, and $\hat{z}$ are orthogonal unit vectors defined as follows:

$\hat{z}$ is along the e momentum

$\hat{y} = [\hat{z}\times\vec{P}_\mu]/|[\hat{z}\times\vec{P}_\mu]|$ is transverse to the e momentum and perpendicular to the "decay plane"

$\hat{x} = \hat{y}\times\hat{z}$ is transverse to the e momentum and in the "decay plane."

The components of $\vec{P}_e$ then are given by

$$\begin{aligned}P_{T_1}(x,\vartheta) &= P_\mu\sin\vartheta\ F_{T_1}(x)/\left(F_{IS}(x) \pm P_\mu\cos\vartheta\ F_{AS}(x)\right) \\ P_{T_2}(x,\vartheta) &= P_\mu\sin\vartheta\ F_{T_2}(x)/\left(F_{IS}(x) \pm P_\mu\ cos\vartheta\ F_{AS}(x)\right) \\ P_L(x,\vartheta) &= \pm F_{IP}(x) + P_\mu\cos\vartheta \\ &\qquad \times F_{AP}(x)/\left(F_{IS}(x) \pm P_\mu\cos\vartheta\ F_{AS}(x)\right)\ ,\end{aligned}$$

where

$$\begin{aligned}F_{T_1}(x) &= \tfrac{1}{12}\left\{-2\left[\xi'' + 12(\rho - \tfrac{3}{4})\right](1-x)x_0\right. \\ &\qquad \left.-3\eta(x^2 - x_0^2) + \eta''(-3x^2 + 4x - x_0^2)\right\} \\ F_{T_2}(x) &= \tfrac{1}{3}\sqrt{x^2 - x_0^2}\left\{3\frac{\alpha'}{A}(1-x) + 2\frac{\beta'}{A}\sqrt{1-x_0^2}\right\} \\ F_{IP}(x) &= \tfrac{1}{54}\sqrt{x^2 - x_0^2}\left\{9\xi'\left(-2x + 2 + \sqrt{1-x_0^2}\right)\right. \\ &\qquad \left.+ 4\xi(\delta - \tfrac{3}{4})(4x - 4 + \sqrt{1-x_0^2})\right\} \\ F_{AP}(x) &= \tfrac{1}{6}\left\{\xi''(2x^2 - x - x_0^2) + 4(\rho - \tfrac{3}{4})\left(4x^2 - 3x - x_0^2\right)\right. \\ &\qquad \left.+2\eta''(1-x)x_0\right\}\ .\end{aligned}$$

For the experimental values of the parameters ρ, ξ, ξ', ξ', δ, η, η', α/A, β/A, α'/A, β'/A, which are not all independent, see the Data Listings below. Experiments in the past have also been analyzed using the parameters a, b, c, a', b', c', α/A, β/A, α'/A, β'/A (and $\eta = (\alpha - 2\beta)/2A$), as defined by Kinoshita and Sirlin [5]. They serve as a model-independent summary of all possible measurements on the decay electron (see Listings below). The relations between the two sets of parameters are

$$\begin{aligned}\rho - \tfrac{3}{4} &= \tfrac{3}{4}(-a + 2c)/A\ , \\ \eta &= (\alpha - 2\beta)/A\ , \\ \eta'' &= (3\alpha + 2\beta)/A\ , \\ \delta - \tfrac{3}{4} &= \tfrac{9}{4}\cdot\frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A}\ , \\ 1 - \xi\frac{\delta}{\rho} &= 4\ \frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A}\ , \\ 1 - \xi' &= [(a + a') + 4(b + b') + 6(c + c')]/A\ , \\ 1 - \xi'' &= (-2a + 20c)/A\ ,\end{aligned}$$

where

$$A = a + 4b + 6c\,.$$

The differential decay probability to obtain a *left-handed* ν_e with (reduced) energy between y and $y + dy$, neglecting radiative corrections as well as the masses of the electron and of the neutrinos, is given by [6]

$$\frac{d\Gamma}{dy} = \frac{m_\mu^5\, G_F}{16\pi^3} \cdot Q_L^{\nu_e} \cdot y^2 \Big\{(1-y) - \omega_L \cdot (y - \tfrac{3}{4})\Big\}\,.$$

Here, $y = 2\ E_{\nu_e}/m_\mu$. $Q_L^{\nu_e}$ and ω_L are parameters. ω_L is the neutrino analog of the spectral shape parameter ρ of Michel. Since in the Standard Model, $Q_L^{\nu_e} = 1$, $\omega_L = 0$, the measurement of $d\Gamma/dy$ has allowed a null-test of the Standard Model (see Listings below).

Matrix element: All results in direct muon decay (energy spectra of the electron and of the neutrinos, polarizations, and angular distributions) and in inverse muon decay (the reaction cross section) at energies well below $m_W c^2$ may be parametrized in terms of amplitudes $g^\gamma_{\varepsilon\mu}$ and the Fermi coupling constant G_F, using the matrix element

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T\\ \varepsilon,\mu=R,L}} g^\gamma_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle . \qquad (2)$$

We use the notation of Fetscher *et al.* [2], who in turn use the sign conventions and definitions of Scheck [7]. Here, $\gamma = S, V, T$ indicates a scalar, vector, or tensor interaction; and $\varepsilon, \mu = R, L$ indicate a right- or left-handed chirality of the electron or muon. The chiralities n and m of the ν_e and $\bar{\nu}_\mu$ are then determined by the values of γ, ε and μ. The particles are represented by fields of definite chirality [8].

As shown by Langacker and London [9], explicit lepton-number nonconservation still leads to a matrix element equivalent to Eq. (2). They conclude that it is not possible, even in principle, to test lepton-number conservation in (leptonic) muon decay if the final neutrinos are massless and are not observed.

The ten complex amplitudes $g^\gamma_{\varepsilon\mu}$ (g^T_{RR} and g^T_{LL} are identically zero) and G_F constitute 19 independent (real) parameters to be determined by experiment. The Standard Model interaction corresponds to one single amplitude g^V_{LL} being unity and all the others being zero.

The (direct) muon decay experiments are compatible with an arbitrary mix of the scalar and vector amplitudes g^S_{LL} and g^V_{LL} – in the extreme even with purely scalar $g^S_{LL} = 2$, $g^V_{LL} = 0$. The decision in favour of the Standard Model comes from the quantitative observation of inverse muon decay, which would be forbidden for pure g^S_{LL} [2].

Experimental determination of V−A: In order to determine the amplitudes $g^\gamma_{\varepsilon\mu}$ uniquely from experiment, the following set of equations, where the left-hand sides represent experimental results, has to be solved.

$$\begin{aligned}
a &= 16(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 + |g^S_{LR} + 6g^T_{LR}|^2\\
a' &= 16(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 - |g^S_{LR} + 6g^T_{LR}|^2\\
\alpha &= 8\mathrm{Re}\left\{g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})\right\}\\
\alpha' &= 8\mathrm{Im}\left\{g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL}) - g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR})\right\}\\
b &= 4(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2\\
b' &= 4(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2\\
\beta &= -4\mathrm{Re}\left\{g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right\}\\
\beta' &= 4\mathrm{Im}\left\{g^V_{RR}g^{S*}_{LL} - g^V_{LL}g^{S*}_{RR}\right\}\\
c &= \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 + |g^S_{LR} - 2g^T_{LR}|^2\right\}\\
c' &= \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 - |g^S_{LR} - 2g^T_{LR}|^2\right\}
\end{aligned}$$

and

$$\begin{aligned}
Q_L^{\nu_e} &= 1 - \left\{\tfrac{1}{4}|g^S_{LR}|^2 + \tfrac{1}{4}|g^S_{LL}|^2 + |g^V_{RR}|^2 + |g^V_{RL}|^2 + 3|g^T_{LR}|^2\right\}\\
\omega_L &= \frac{3}{4}\,\frac{\{|g^S_{RR}|^2 + 4|g^V_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\}}{|g^S_{RL}|^2 + |g^S_{RR}|^2 + 4|g^V_{LL}|^2 + 4|g^V_{LR}|^2 + 12|g^T_{RL}|^2\}}\,.
\end{aligned}$$

It has been noted earlier by C. Jarlskog [10], that certain experiments observing the decay electron are especially informative if the yield the V-A values. The complete solution is now found as follows. Fetscher *et al.* [2] introduced four probabilities $Q_{\varepsilon\mu}(\varepsilon, \mu = R, L)$ for the decay of a μ-handed muon into an ε-handed electron and showed that there exist upper bounds on Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound on Q_{LL}. These probabilities are given in terms of the $g^\gamma_{\varepsilon\mu}$'s by

$$Q_{\varepsilon\mu} = \tfrac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1 - \delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2\,, \qquad (3)$$

where $\delta_{\varepsilon\mu} = 1$ for $\varepsilon = \mu$, and $\delta_{\varepsilon\mu} = 0$ for $\varepsilon \neq \mu$. They are related to the parameters a, b, c, a', b', and c' by

$$\begin{aligned}
Q_{RR} &= 2(b + b')/A\,,\\
Q_{LR} &= [(a - a') + 6(c - c')]/2A\,,\\
Q_{RL} &= [(a + a') + 6(c + c')]/2A\,,\\
Q_{LL} &= 2(b - b')/A\,,
\end{aligned}$$

with $A = 16$. In the Standard Model, $Q_{LL} = 1$ and the others are zero.

Since the upper bounds on Q_{RR}, Q_{LR}, and Q_{RL} are found to be small, and since the helicity of the ν_μ in pion decay is known from experiment [11,12] to very high precision to be -1 [13], the cross section S of *inverse* muon decay, normalized to the V-A value, yields [2]

$$|g^S_{LL}|^2 \leq 4(1 - S) \qquad (4)$$

and

$$|g^V_{LL}|^2 = S\,. \qquad (5)$$

Thus the Standard Model assumption of a pure V-A leptonic charged weak interaction of e and μ is derived (within errors) from experiments at energies far below mass of the $W^{\pm}$: Eq. (5) gives a lower limit for V-A, and Eqs. (3) and (4) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR}+Q_{RL} = (1-\xi')/2$ and $Q_{RR}+Q_{LR} = \frac{1}{2}(1+\xi/3-16\ \xi\delta/9)$. Table 1 gives the current experimental limits on the magnitudes of the $g^{\gamma}_{\epsilon\mu}$'s.

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 16), are given by Burkard *et al.* [17].

Table 1. Coupling constants $g^{\gamma}_{\epsilon\mu}$. Ninety-percent confidence level experimental limits. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 14, and the others are from Ref. 15. The experimental uncertainty on the muon polarization in pion decay is included.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$

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μ DECAY PARAMETERS

ρ PARAMETER

(V−A) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[27] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[27] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[27] PEOPLES	66	ASPK	+	20–53 MeV e^+

[27] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

(V−A) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[28] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.012±0.015±0.003	5.3M	[29] BURKARD	85B	CNTR	+	9–53 MeV e^+
0.011±0.081±0.026	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
−0.7 ±0.5	170k	[30] FRYBERGER	68	ASPK	+	25–53 MeV e^+
−0.7 ±0.6	280k	[30] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.05 ±0.5	800k	[30] PEOPLES	66	ASPK	+	20–53 MeV e^+
−2.0 ±0.9	9213	[31] PLANO	60	HBC	+	Whole spectrum

[28] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[29] $\alpha = \alpha' = 0$ assumed.

[30] ρ constrained = 0.75.

[31] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

(V−A) theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[32] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[33] VOSSLER	69			
0.752 ±0.009	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.782 ±0.031		KRUGER	61			
0.78 ±0.05	8364	PLANO	60	HBC	+	Whole spectrum

[32] BALKE 88 uses $\rho = 0.752 \pm 0.003$.

[33] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

$|(\xi$ PARAMETER$)\times(\mu$ LONGITUDINAL POLARIZATION$)|$

(V−A) theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.0013±0.0030±0.0053		[34] IMAZATO	92	SPEC	+	$K^+ \rightarrow \mu^+\nu_{\mu}$
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		See AKHMANOV 68
0.903 ±0.027		[35] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[34] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_{\mu}| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.

[35] Depolarization by medium not known sufficiently well.

$\xi \times (\mu$ LONGITUDINAL POLARIZATION$) \times \delta / \rho$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99682	90	[36] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[37] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[36] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.

[37] STOKER 85 find $(\xi P_{\mu}\delta/\rho)$ >0.9955 and >0.9966, where the first limit is from new μ spin-rotation data and the second is from combination with CARR 83 data. In V−A theory, $(\delta/\rho) = 1.0$.

ξ' = LONGITUDINAL POLARIZATION OF e^+

(V−A) theory predicts the longitudinal polarization = ±1 for $e^{\pm}$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998±0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ±0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ±0.3[illegible]		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ±0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ±0.30		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[38] BURKARD	85	CNTR	+	Bhabha + annihil

[38] BURKARD 85 measure $(\xi''$-$\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.016±0.021±0.01	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[39] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15 ±50 ±14	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[39] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
− 0.2± 4.3		[40] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−47 ±50 ±14	5.3M	[41] BURKARD	85B	CNTR	+	9–53 MeV e^+

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[41] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.9± 6.2		[42] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2 ±17 ±6	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[42] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.5± 6.3		[43] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17 ±17 ±6	5.3M	[44] BURKARD	85B	CNTR	+	9–53 MeV e^+

[43] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[44] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[45] BURKARD	85B	FIT

[45] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3±4.1	[46] BURKARD	85B	FIT

[46] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[47] BURKARD	85B	FIT

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[48] BURKARD	85B	FIT

[48] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.5±2.0	[49] BURKARD	85B	FIT

[49] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\overline{\eta}$ PARAMETER

($V-A$) theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.02 ±0.08 OUR AVERAGE					
−0.014±0.090	EICHENBER...	84	ELEC	+	ρ free
+0.09 ±0.14	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.035±0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

GORDEEV	97	PAN 60 1164	V.A. Gordeev+	(PNPI)
		Translated from YAF 60 1291.		
ABELA	96	PRL 77 1950	+Bagaturia+	(PSI, ZURI, HEIDH, TBIL, YALE+)
HONECKER	96	PRL 76 200	+Dohmen, Haan, Junker+	(SINDRUM II Collab.)
DOHMEN	93	PL B317 631	+Groth, Heer+	(PSI SINDRUM-II Collab.)
FREEDMAN	93	PR D47 811	+Fujikawa, Napolitano, Nelson+	(LAMPF E645 Collab.)
NI	93	PR D48 1976	+Arnold, Chmely+	(LAMPF Crystal-Box Collab.)
IMAZATO	92	PRL 69 877	+Kawashima, Tanaka+	(KEK, INUS, TOKY, TOKMS)
BARANOV	91	SJNP 53 802	+Vanko, Glazov, Evtukhovich+	(JINR)
		Translated from YAF 53 1302.		
KRAKAUER	91B	PL B263 534	+Talaga, Allen, Chen, Doe+	(UMD, UCI, LANL)
MATTHIAS	91	PRL 66 2716	+Ahn+	(YALE, HEIDP, WILL, GSI, VILL, BNL)
Also	91B	PRL 67 932 erratum	Matthias, Ahn+	(YALE, HEIDP, WILL, GSI, VILL, BNL)
HUBER	90B	PR D41 2709	+	(WYOM, VICT, ARIZ, ROCH, TRIU, SFRA, BRCO)
AHMAD	88	PR D38 2102	+Azuelos+	(TRIU, VICT, VPI, BRCO, MONT, CNRC)
Also	87	PRL 59 970	Ahmad+	(TRIU, VPI, VICT, BRCO, MONT, CNRC)
BALKE	88	PR D37 587	+Gidal, Jodidio+	(LBL, UCB, COLO, NWES, TRIU)
BELLGARDT	88	NP B299 1	+Otter, Eichler+	(SINDRUM Collab.)
BOLTON	88	PR D38 2077	+Cooper, Frank, Hallin+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 56 2461	Bolton, Bowman, Cooper+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 57 3241	Grosnick, Wright, Bolton+	(CHIC, LANL, STAN, TEMP)
BELTRAMI	87	PL B194 326	+Burkard, Von Dincklage+	(ETH, SIN, MANZ)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
BEER	86	PRL 57 671	+Marshall, Mason+	(VICT, TRIU, WYOM)
BELTRAMI	86	NP A451 679	+Aas, Beer, Dechambrier, Goudsmit+	(ETH, FRIB)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
BERTL	85	NP B260 1	+Egli, Eichler+	(SINDRUM Collab.)
BRYMAN	85	PRL 55 465	+	(TRIU, CNRC, BRCO, LANL, CHIC, CARL+)
BURKARD	85	PL 150B 242	+Corriveau, Egger+	(ETH, SIN, MANZ)
BURKARD	85B	PL 160B 343	+Corriveau, Egger+	(ETH, SIN, MANZ)
Also	81B	PR D24 2004	Corriveau, Egger, Fetscher+	(ETH, SIN, MANZ)
Also	83B	PL 129B 260	Corriveau, Egger, Fetscher+	(ETH, SIN, MANZ)
HUGHES	85	CNPP 14 341	+Kinoshita	(YALE, CORN)
STOKER	85	PRL 54 1887	+Balke, Carr, Gidal+	(LBL, NWES, TRIU)
BARDIN	84	PL 137B 135	+Duclos, Magnon+	(SACL, CERN, BGNA, FIRZ)
BERTL	84	PL 140B 299	+Eichler, Felawka+	(SINDRUM Collab.)
BOLTON	84	PRL 53 1415	+Bowman, Carlini+	(LANL, CHIC, STAN, TEMP)
EICHENBER...	84	NP A412 523	Eichenberger, Engfer, VanderSchaff	(ZURI)
GIOVANETTI	84	PR D29 343	+Dey, Eckhause, Hart+	(WILL)
KINOSHITA	84	PRL 52 717	+Nizic, Okamoto	(CORN)
AZUELOS	83	PRL 51 164	+Depommier, Leroy, Martin+	(MONT, TRIU, BRCO)
Also	77	PRL 39 1113	Depommier+	(MONT, BRCO, TRIU, VICT, MELB)
BERGSMA	83	PL 122B 465	+Dorenbosch, Jonker+	(CHARM Collab.)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
KINNISON	82	PR D25 2846	+Anderson, Matis, Wright+	(EFI, STAN, LANL)
Also	79	PRL 42 556	Bowman, Cooper, Hamm+	(LASL, EFI, STAN)
KLEMPT	82	PR D25 652	+Schulze, Wolf, Camani, Gygax+	(MANZ, ETH)
MARIAM	82	PRL 49 993	+Beer, Bolton, Egan, Gardner+	(YALE, HEIDH, BERN)
MARSHALL	82	PR D25 1174	+Warren, Oram, Kiefl	(BRCO)
COMBLEY	81	PRPL 68 93	+Farley, Picasso	(SHEF, RMCS, CERN)
NEMETHY	81	CNPP 10 147	+Hughes	(LBL, YALE)
ABELA	80	PL 95B 318	+Backenstoss, Simons, Wuest+	(BASL, KARLK, KARLE)
BADERT...	80	LNC 28 401	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
Also	82	NP A377 406	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
JONKER	80	PL 93B 203	+Panman, Udo, Allaby+	(CHARM Collab.)
SCHAAF	80	NP A340 249	+Engfer, Povel, Dey+	(ZURI, ETH, SIN)
Also	77	PL 72B 183	Povel, Dey, Walter, Pfeiffer+	(ZURI, ETH, SIN)
WILLIS	80	PRL 44 522	+Hughes+	(YALE, LBL, LASL, SACL, SIN, CNRC+)
Also	80B	PRL 45 1370	Willis+	(YALE, LBL, LASL, SACL, SIN, CNRC+)
BAILEY	79	NP B150 1		(CERN, DARE, MANZ)
FARLEY	79	ARNPS 29 243	+Picasso	(RMCS, CERN)
BADERT...	78	PL 79B 371	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
BAILEY	78	JPG 4 345		(DARE, BERN, SHEF, MANZ, RMCS, CERN, BIRM)
Also	79	NP B150 1	Bailey	(CERN, DARE, MANZ)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BOWMAN	78	PRL 41 442	+Cheng, Li, Matis	(LASL, IAS, CMU, EFI)
CAMANI	78	PL 77B 326	+Gygax, Klempt, Schenck, Schulze+	(ETH, MANZ)
BADERT...	77	PRL 39 1385	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
BAILEY	77	PL 67B 225	+	(CERN Muon Storage Ring Collab.)
Also	77C	PL 68B 191	Bailey+	(CERN, DARE, BERN, SHEF, MANZ+)
Also	75	PL 55B 420	Bailey+	(CERN Muon Storage Ring Collab., BIRM)
CALMET	77	RMP 49 21	+Narison, Perrottet+	(CPPM)
CASPERSON	77	PRL 38 956	+Crane+	(BERN, HEIDH, LASL, WYOM, YALE)
DEPOMMIER	77	PRL 39 1113	+	(MONT, BRCO, TRIU, VICT, MELB)
BALANDIN	74	JETP 40 811	+Grebenyuk, Zinov, Konin, Ponomarev	(JINR)
		Translated from ZETF 67 1631.		
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DUCLOS	73	PL 47B 491	+Magnon, Picard	(SACL)
EICHTEN	73	PL 46B 281	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BRYMAN	72	PRL 28 1469	+Blecher, Gotow, Powers	(VPI)
CROWE	72	PR D5 2145	+Hague, Rothberg, Schenck+	(LBL, WASH)
CRANE	71	PRL 27 474	+Casperson, Crane, Egan, Hughes+	(YALE)
DERENZO	69	PR 181 1854		(EFI)
VOSSLER	69	NC 63A 423		(EFI)
AKHMANOV	68	SJNP 6 230	+Gurevich, Dobretsov, Makarina+	(KIAE)
		Translated from YAF 6 316.		

BAILEY 68 PL 28B 287 +Bartl, VonBochmann, Brown, Farley+ (CERN)
Also 72 NC 9A 369 Bailey, Bartl, VonBochmann, Brown+ (CERN)
FRYBERGER 68 PR 166 1379 (EFI)
BOGART 67 PR 156 1405 +Dicapua, Nemethy, Strelzoff (COLU)
SCHWARTZ 67 PR 162 1306 (EFI)
SHERWOOD 67 PR 156 1475 (EFI)
PEOPLES 66 Nevis 147 unpub. (COLU)
BLOOM 64 PL 8 87 +Dick, Feuvrais, Henry, Macq, Spighel (CERN)
DUCLOS 64 PL 9 62 +Heintze, DeRujula, Soergel (CERN)
GUREVICH 64 PL 11 185 +Makarina+ (KIAE)
BUHLER 63 PL 7 368 +Cabibbo, Fidecaro, Massam, Muller+ (CERN)
MEYER 63 PR 132 2693 +Anderson, Bleser, Lederman+ (COLU)
CHARPAK 62 PL 1 16 +Farley, Garwin+ (CERN)
CONFORTO 62 NC 26 261 +Conversi, Dilella+ (INFN, ROMA, CERN)
ALI-ZADE 61 JETP 13 313 +Gurevich, Nikolski
Translated from ZETF 40 452.
CRITTENDEN 61 PR 121 1823 +Walker, Ballam (WISC, MSU)
KRUGER 61 UCRL 9322 unpub. (LRL)
GUREVICH 60 JETP 10 225 +Nikolski, Surkova (ITEP)
Translated from ZETF 37 318.
PLANO 60 PR 119 1400 (COLU)
ASHKIN 59 NC 14 1266 +Fazzini, Fidecaro, Lipman, Merrison+ (CERN)
BARDON 59 PRL 2 56 +Berley, Lederman (COLU)
LEE 59 PRL 3 55 +Samios (COLU)

$\boxed{\tau}$

$J = \frac{1}{2}$

τ discovery paper was PERL 75. $e^+e^- \rightarrow \tau^+\tau^-$ cross-section threshold behavior and magnitude are consistent with pointlike spin-1/2 Dirac particle. BRANDELIK 78 ruled out pointlike spin-0 or spin-1 particle. FELDMAN 78 ruled out $J = 3/2$. KIRKBY 79 also ruled out J=integer, $J = 3/2$.

τ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$1777.05^{+0.29}_{-0.26}$ OUR AVERAGE				
1778.2 ±0.8 ±1.2		ANASTASSOV 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
$1776.96^{+0.18+0.25}_{-0.21-0.17}$	65	[1] BAI 96	BES	$E^{ee}_{\rm cm}$= 3.54–3.57 GeV
1777.8 ±0.7 ±1.7	35k	[2] BALEST 93	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1776.3 ±2.4 ±1.4	11k	[3] ALBRECHT 92M	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
$1783\ ^{+3}_{-4}$	692	[4] BACINO 78B	DLCO	$E^{ee}_{\rm cm}$= 3.1–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1776.9\ ^{+0.4}_{-0.5}$ ±0.2	14	[5] BAI 92	BES	Repl. by BAI 96

[1] BAI 96 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ at different energies near threshold.

[2] BALEST 93 fit spectra of minimum kinematically allowed τ mass in events of the type $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\pi^+ n\pi^0 \nu_\tau)(\pi^- m\pi^0 \nu_\tau)$ $n \leq 2$, $m \leq 2$, $1 \leq n+m \leq 3$. If $m_{\nu_\tau} \neq 0$, result increases by ($m^2_{\nu_\tau}$/1100 MeV).

[3] ALBRECHT 92M fit τ pseudomass spectrum in $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[4] BACINO 78B value comes from $e^\pm X^\mp$ threshold. Published mass 1782 MeV increased by 1 MeV using the high precision $\psi(2S)$ mass measurement of ZHOLENTZ 80 to eliminate the absolute SPEAR energy calibration uncertainty.

[5] BAI 92 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ near threshold using $e\mu$ events.

τ MEAN LIFE

VALUE (10^{-15} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
290.0± 1.2 OUR AVERAGE				
290.1± 1.5± 1.1		BARATE 97R	ALEP	1989–1994 LEP runs
291.4± 3.0		ABREU 96B	DLPH	1991–1993 LEP runs
290.1± 4.0	34k	ACCIARRI 96K	L3	1994 LEP run
289.2± 1.7± 1.2		ALEXANDER 96E	OPAL	1990–1994 LEP runs
289.0± 2.8± 4.0	57.4k	BALEST 96	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
291.2± 2.0± 1.2		BARATE 97I	ALEP	Repl. by BARATE 97R
297 ± 9 ± 5	1671	ABE 95Y	SLD	1992–1993 SLC runs
293 ± 9 ±12	5743	ADRIANI 93M	L3	1991 LEP run
304 ± 14 ± 7	4100	BATTLE 92	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
309 ± 23 ±30	2817	ADEVA 91F	L3	1990 LEP run
301 ± 29	3780	KLEINWORT 89	JADE	$E^{ee}_{\rm cm}$= 35–46 GeV
288 ± 16 ±17	807	AMIDEI 88	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
306 ± 20 ±14	695	BRAUNSCH... 88C	TASS	$E^{ee}_{\rm cm}$= 36 GeV
299 ± 15 ±10	1311	ABACHI 87C	HRS	$E^{ee}_{\rm cm}$= 29 GeV
295 ± 14 ±11	5696	ALBRECHT 87P	ARG	$E^{ee}_{\rm cm}$= 9.3–10.6 GeV
309 ± 17 ± 7	3788	BAND 87B	MAC	$E^{ee}_{\rm cm}$= 29 GeV
325 ± 14 ±18	8470	BEBEK 87C	CLEO	$E^{ee}_{\rm cm}$= 10.5 GeV
460 ±190	102	FELDMAN 82	MRK2	$E^{ee}_{\rm cm}$= 29 GeV

τ MAGNETIC MOMENT ANOMALY

$\mu_\tau/(e\hbar/2m_\tau)-1 = (g_\tau-2)/2$

For a theoretical calculation [$(g_\tau-2)/2 = 11773(3) \times 10^{-7}$], see SAMUEL 91B.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> −0.052 and < 0.058 (CL = 95%) OUR LIMIT				
> −0.052 and < 0.058	95	ACCIARRI 98E	L3	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> −0.068 and < 0.065	95	[6] ACKERSTAFF 98N	OPAL	1990–1995 LEP runs
> −0.004 and < 0.006	95	[7] ESCRIBANO 97	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
<0.01	95	[8] ESCRIBANO 93	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
<0.12	90	GRIFOLS 91	RVUE	$Z \rightarrow \tau\tau\gamma$ at LEP
<0.023	95	[9] SILVERMAN 83	RVUE	$e^+e^- \rightarrow \tau^+\tau^-$ at PETRA

[6] ACKERSTAFF 98N use $Z \rightarrow \tau^+\tau^-\gamma$ events. The limit applies to an average of the form factor for off-shell τ's having p^2 ranging from m^2_τ to $(M_Z-m_\tau)^2$.

[7] ESCRIBANO 97 use preliminary experimental results.

[8] ESCRIBANO 93 limit derived from $\Gamma(Z \rightarrow \tau^+\tau^-)$, and is on the absolute value of the magnetic moment anomaly.

[9] SILVERMAN 83 limit is derived from $e^+e^- \rightarrow \tau^+\tau^-$ total cross-section measurements for q^2 up to (37 GeV)^2.

τ ELECTRIC DIPOLE MOMENT (d_τ)

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-16} $e$cm)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> −3.1 and < 3.1 (CL = 95%) OUR LIMIT				
> −3.1 and < 3.1	95	ACCIARRI 98E	L3	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> −3.8 and < 3.6	95	[10] ACKERSTAFF 98N	OPAL	1990–1995 LEP runs
<0.11	95	[11,12] ESCRIBANO 97	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
<0.5	95	[13] ESCRIBANO 93	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
<7	90	GRIFOLS 91	RVUE	$Z \rightarrow \tau\tau\gamma$ at LEP
<1.6	90	DELAGUILA 90	RVUE	$e^+e^- \rightarrow \tau^+\tau^-$ $E^{ee}_{\rm cm}$= 35 GeV

[10] ACKERSTAFF 98N use $Z \rightarrow \tau^+\tau^-\gamma$ events. The limit applies to an average of the form factor for off-shell τ's having p^2 ranging from m^2_τ to $(M_Z-m_\tau)^2$.

[11] ESCRIBANO 97 derive the relationship $|d_\tau| = \cot\theta_W\, |d^W_\tau|$ using effective Lagrangian methods, and use a conference result $|d^W_\tau| < 5.8 \times 10^{-18}$ $e$cm at 95% CL (L. Silvestris, ICHEP96) to obtain this result.

[12] ESCRIBANO 97 use preliminary experimental results.

[13] ESCRIBANO 93 limit derived from $\Gamma(Z \rightarrow \tau^+\tau^-)$, and is on the absolute value of the electric dipole moment.

τ WEAK DIPOLE MOMENT (d^W_τ)

A nonzero value is forbidden by CP invariance.

Re(d^W_τ)

VALUE (10^{-17} $e$cm)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.56	95	ACKERSTAFF 97L	OPAL	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.0	90	[14] ACCIARRI 98C	L3	1991–1995 LEP runs
<0.78	95	[15] AKERS 95F	OPAL	Repl. by ACKERSTAFF 97L
<1.5	95	[15] BUSKULIC 95C	ALEP	1990–1992 LEP runs
<7.0	95	[15] ACTON 92F	OPAL	$Z \rightarrow \tau^+\tau^-$ at LEP
<3.7	95	[15] BUSKULIC 92J	ALEP	Repl. by BUSKULIC 95C

[14] ACCIARRI 98C limit is on the absolute value of the real part of the weak dipole moment.

[15] Limit is on the absolute value of the real part of the weak dipole moment, and applies for $q^2 = m^2_Z$.

Im(d^W_τ)

VALUE (10^{-17} $e$cm)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.5	95	ACKERSTAFF 97L	OPAL	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.5	95	[16] AKERS 95F	OPAL	Repl. by ACKERSTAFF 97L

[16] Limit is on the absolute value of the imaginary part of the weak dipole moment, and applies for $q^2 = m^2_Z$.

τ WEAK ANOMALOUS MAGNETIC DIPOLE MOMENT (α^W_τ)

Re(α^W_τ)

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<4.5 × 10^{-3}	90	[17] ACCIARRI 98C	L3	1991–1995 LEP runs

[17] ACCIARRI 98C limit is on the absolute value of the real part of the weak anomalous magnetic dipole moment.

Im(α_τ^W)

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.9 \times 10^{-3}$	90	[18] ACCIARRI 98C	L3	1991–1995 LEP runs

[18] ACCIARRI 98C limit is on the absolute value of the imaginary part of the weak anomalous magnetic dipole moment.

τ^- DECAY MODES

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Modes with one charged particle			
Γ_1	particle$^-$ ≥ 0 neutrals $\geq 0 K_L^0 \nu_\tau$ ("1-prong")		(84.71 ± 0.13) %	S=1.2
Γ_2	particle$^-$ ≥ 0 neutrals $\geq 0 K^0 \nu_\tau$		(85.30 ± 0.13) %	S=1.2
Γ_3	$\mu^- \overline{\nu}_\mu \nu_\tau$	[a]	(17.37 ± 0.09) %	
Γ_4	$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$	[b]	$(3.0 \pm 0.6) \times 10^{-3}$	
Γ_5	$e^- \overline{\nu}_e \nu_\tau$	[a]	(17.81 ± 0.07) %	
Γ_6	$h^- \geq 0$ neutrals $\geq 0 K_L^0\ \nu_\tau$		(49.52 ± 0.16) %	S=1.2
Γ_7	$h^- \geq 0 K_L^0\ \nu_\tau$		(12.32 ± 0.12) %	S=1.5
Γ_8	$h^- \nu_\tau$		(11.79 ± 0.12) %	S=1.5
Γ_9	$\pi^- \nu_\tau$	[a]	(11.08 ± 0.13) %	S=1.4
Γ_{10}	$K^- \nu_\tau$	[a]	$(7.1 \pm 0.5) \times 10^{-3}$	
Γ_{11}	$h^- \geq 1$ neutrals ν_τ		(36.91 ± 0.17) %	S=1.2
Γ_{12}	$h^- \pi^0 \nu_\tau$		(25.84 ± 0.14) %	S=1.1
Γ_{13}	$\pi^- \pi^0 \nu_\tau$	[a]	(25.32 ± 0.15) %	S=1.1
Γ_{14}	$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$	
Γ_{15}	$K^- \pi^0 \nu_\tau$	[a]	$(5.2 \pm 0.5) \times 10^{-3}$	
Γ_{16}	$h^- \geq 2\pi^0 \nu_\tau$		(10.79 ± 0.16) %	S=1.2
Γ_{17}	$h^- 2\pi^0 \nu_\tau$		(9.39 ± 0.14) %	S=1.2
Γ_{18}	$h^- 2\pi^0 \nu_\tau$ (ex.K^0)		(9.23 ± 0.14) %	S=1.2
Γ_{19}	$\pi^- 2\pi^0 \nu_\tau$ (ex.K^0)	[a]	(9.15 ± 0.15) %	S=1.2
Γ_{20}	$K^- 2\pi^0 \nu_\tau$ (ex.K^0)	[a]	$(8.0 \pm 2.7) \times 10^{-4}$	
Γ_{21}	$h^- \geq 3\pi^0 \nu_\tau$		(1.40 ± 0.11) %	S=1.1
Γ_{22}	$h^- 3\pi^0 \nu_\tau$		(1.23 ± 0.10) %	S=1.1
Γ_{23}	$\pi^- 3\pi^0 \nu_\tau$ (ex.K^0)	[a]	(1.11 ± 0.14) %	
Γ_{24}	$K^- 3\pi^0 \nu_\tau$ (ex.K^0)	[a]	$(4.3\ ^{+10.0}_{-2.9}) \times 10^{-4}$	
Γ_{25}	$h^- 4\pi^0 \nu_\tau$ (ex.K^0)		$(1.7 \pm 0.6) \times 10^{-3}$	
Γ_{26}	$h^- 4\pi^0 \nu_\tau$ (ex.K^0,η)	[a]	$(1.1 \pm 0.6) \times 10^{-3}$	
Γ_{27}	$K^- \geq 0\pi^0\ \geq 0 K^0\ \nu_\tau$		(1.66 ± 0.10) %	
Γ_{28}	$K^- \geq 1\ (\pi^0$ or $K^0)\ \nu_\tau$		$(9.5 \pm 1.0) \times 10^{-3}$	
	Modes with K^0's			
Γ_{29}	K^0(particles)$^- \nu_\tau$		(1.66 ± 0.09) %	S=1.4
Γ_{30}	$h^- \overline{K}^0 \geq 0$ neutrals $\geq 0 K_L^0 \nu_\tau$		(1.62 ± 0.09) %	S=1.4
Γ_{31}	$h^- \overline{K}^0 \nu_\tau$		$(9.9 \pm 0.8) \times 10^{-3}$	S=1.5
Γ_{32}	$\pi^- \overline{K}^0 \nu_\tau$	[a]	$(8.3 \pm 0.8) \times 10^{-3}$	S=1.4
Γ_{33}	$\pi^- \overline{K}^0$ (non-$K^*(892)^-$) ν_τ		$< 1.7 \times 10^{-3}$	CL=95%
Γ_{34}	$K^- K^0 \nu_\tau$	[a]	$(1.59 \pm 0.24) \times 10^{-3}$	
Γ_{35}	$h^- \overline{K}^0 \pi^0 \nu_\tau$		$(5.5 \pm 0.5) \times 10^{-3}$	
Γ_{36}	$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	[a]	$(3.9 \pm 0.5) \times 10^{-3}$	
Γ_{37}	$\overline{K}^0 \rho^- \nu_\tau$		$(1.9 \pm 0.7) \times 10^{-3}$	
Γ_{38}	$K^- K^0 \pi^0 \nu_\tau$	[a]	$(1.51 \pm 0.29) \times 10^{-3}$	
Γ_{39}	$\pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau$		$(6 \pm 4) \times 10^{-4}$	
Γ_{40}	$K^- K^0 \pi^0 \pi^0 \nu_\tau$		$< 3.9 \times 10^{-4}$	CL=95%
Γ_{41}	$\pi^- K^0 \overline{K}^0 \nu_\tau$	[a]	$(1.21 \pm 0.21) \times 10^{-3}$	S=1.2
Γ_{42}	$\pi^- K_S^0 K_S^0 \nu_\tau$		$(3.0 \pm 0.5) \times 10^{-4}$	S=1.2
Γ_{43}	$\pi^- K_S^0 K_L^0 \nu_\tau$		$(6.0 \pm 1.0) \times 10^{-4}$	S=1.2
Γ_{44}	$\pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%
Γ_{45}	$\pi^- K_S^0 K_L^0 \pi^0 \nu_\tau$		$(3.1 \pm 1.2) \times 10^{-4}$	
Γ_{46}	$K^- K^0 \geq 0$ neutrals ν_τ		$(3.1 \pm 0.4) \times 10^{-3}$	
Γ_{47}	$K^0 h^+ h^- h^- \geq 0$ neutrals ν_τ		$< 1.7 \times 10^{-3}$	CL=95%
Γ_{48}	$K^0 h^+ h^- h^- \nu_\tau$		$(2.3 \pm 2.0) \times 10^{-4}$	
	Modes with three charged particles			
Γ_{49}	$h^- h^- h^+ \geq 0$neut. ν_τ ("3-prong")		(15.18 ± 0.13) %	S=1.2
Γ_{50}	$h^- h^- h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^+ \pi^-$)		(14.60 ± 0.13) %	S=1.2
Γ_{51}	$\pi^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		(14.60 ± 0.14) %	
Γ_{52}	$h^- h^- h^+ \nu_\tau$		(9.96 ± 0.10) %	S=1.1
Γ_{53}	$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.62 ± 0.10) %	S=1.1
Γ_{54}	$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)		(9.57 ± 0.10) %	S=1.1
Γ_{55}	$\pi^- \pi^+ \pi^- \nu_\tau$		(9.56 ± 0.11) %	S=1.1
Γ_{56}	$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)		(9.52 ± 0.11) %	S=1.1
Γ_{57}	$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0,ω)	[a]	(9.23 ± 0.11) %	S=1.1
Γ_{58}	$h^- h^- h^+ \geq 1$ neutrals ν_τ		(5.18 ± 0.11) %	S=1.2
Γ_{59}	$h^- h^- h^+ \geq 1$ neutrals ν_τ (ex. $K_S^0 \to \pi^+ \pi^-$)		(4.98 ± 0.11) %	S=1.2
Γ_{60}	$h^- h^- h^+ \pi^0 \nu_\tau$		(4.50 ± 0.09) %	S=1.1
Γ_{61}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.31 ± 0.09) %	S=1.1
Γ_{62}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)		(2.59 ± 0.09) %	
Γ_{63}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		(4.35 ± 0.10) %	
Γ_{64}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		(4.22 ± 0.10) %	
Γ_{65}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0,ω)	[a]	(2.49 ± 0.10) %	
Γ_{66}	$h^- (\rho\pi)^0 \nu_\tau$		(2.88 ± 0.35) %	
Γ_{67}	$(a_1(1260) h)^- \nu_\tau$		< 2.0 %	CL=95%
Γ_{68}	$h^- \rho \pi^0 \nu_\tau$		(1.35 ± 0.20) %	
Γ_{69}	$h^- \rho^+ h^- \nu_\tau$		$(4.5 \pm 2.2) \times 10^{-3}$	
Γ_{70}	$h^- \rho^- h^+ \nu_\tau$		(1.17 ± 0.23) %	
Γ_{71}	$h^- h^- h^+ 2\pi^0 \nu_\tau$		$(5.4 \pm 0.4) \times 10^{-3}$	
Γ_{72}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0)		$(5.3 \pm 0.4) \times 10^{-3}$	
Γ_{73}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0,ω,η)	[a]	$(1.1 \pm 0.4) \times 10^{-3}$	
Γ_{74}	$h^- h^- h^+ \geq 3\pi^0 \nu_\tau$	[a]	$(1.4\ ^{+0.9}_{-0.7}) \times 10^{-3}$	S=1.5
Γ_{75}	$h^- h^- h^+ 3\pi^0 \nu_\tau$		$(2.9 \pm 0.8) \times 10^{-4}$	
Γ_{76}	$K^- h^+ h^- \geq 0$ neutrals ν_τ		$(5.4 \pm 0.7) \times 10^{-3}$	S=1.1
Γ_{77}	$K^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		$(3.1 \pm 0.6) \times 10^{-3}$	S=1.1
Γ_{78}	$K^- \pi^+ \pi^- \nu_\tau$		$(2.3 \pm 0.4) \times 10^{-3}$	
Γ_{79}	$K^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)	[a]	$(1.8 \pm 0.5) \times 10^{-3}$	
Γ_{80}	$K^- \pi^+ \pi^- \pi^0 \nu_\tau$		$(8 \pm 4) \times 10^{-4}$	
Γ_{81}	$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)	[a]	$(2.4\ ^{+4.3}_{-1.6}) \times 10^{-4}$	
Γ_{82}	$K^- \pi^+ K^- \geq 0$ neut. ν_τ		$< 9 \times 10^{-4}$	CL=95%
Γ_{83}	$K^- K^+ \pi^- \geq 0$ neut. ν_τ		$(2.3 \pm 0.4) \times 10^{-3}$	
Γ_{84}	$K^- K^+ \pi^- \nu_\tau$	[a]	$(1.61 \pm 0.26) \times 10^{-3}$	
Γ_{85}	$K^- K^+ \pi^- \pi^0 \nu_\tau$	[a]	$(6.9 \pm 3.0) \times 10^{-4}$	
Γ_{86}	$K^- K^+ K^- \geq 0$ neut. ν_τ		$< 2.1 \times 10^{-3}$	CL=95%
Γ_{87}	$K^- K^+ K^- \nu_\tau$		$< 1.9 \times 10^{-4}$	CL=90%
Γ_{88}	$\pi^- K^+ \pi^- \geq 0$ neut. ν_τ		$< 2.5 \times 10^{-3}$	CL=95%
Γ_{89}	$e^- e^- e^+ \overline{\nu}_e \nu_\tau$		$(2.8 \pm 1.5) \times 10^{-5}$	
Γ_{90}	$\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau$		$< 3.6 \times 10^{-5}$	CL=90%
	Modes with five charged particles			
Γ_{91}	$3h^- 2h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^- \pi^+$) ("5-prong")		$(9.7 \pm 0.7) \times 10^{-4}$	
Γ_{92}	$3h^- 2h^+ \nu_\tau$ (ex.K^0)	[a]	$(7.5 \pm 0.7) \times 10^{-4}$	
Γ_{93}	$3h^- 2h^+ \pi^0 \nu_\tau$ (ex.K^0)	[a]	$(2.2 \pm 0.5) \times 10^{-4}$	
Γ_{94}	$3h^- 2h^+ 2\pi^0 \nu_\tau$		$< 1.1 \times 10^{-4}$	CL=90%
	Miscellaneous other allowed modes			
Γ_{95}	$(5\pi)^- \nu_\tau$		$(7.4 \pm 0.7) \times 10^{-3}$	
Γ_{96}	$4h^- 3h^+ \geq 0$ neutrals ν_τ ("7-prong")		$< 2.4 \times 10^{-6}$	CL=90%
Γ_{97}	$K^*(892)^- \geq 0(h^0 \neq K_S^0) \nu_\tau$		(1.94 ± 0.31) %	
Γ_{98}	$K^*(892)^- \geq 0$ neutrals ν_τ		(1.33 ± 0.13) %	
Γ_{99}	$K^*(892)^- \nu_\tau$		(1.28 ± 0.08) %	
Γ_{100}	$K^*(892)^0 K^- \geq 0$ neutrals ν_τ		$(3.2 \pm 1.4) \times 10^{-3}$	
Γ_{101}	$K^*(892)^0 K^- \nu_\tau$		$(2.1 \pm 0.4) \times 10^{-3}$	
Γ_{102}	$\overline{K}^*(892)^0 \pi^- \geq 0$ neutrals ν_τ		$(3.8 \pm 1.7) \times 10^{-3}$	
Γ_{103}	$\overline{K}^*(892)^0 \pi^- \nu_\tau$		$(2.2 \pm 0.5) \times 10^{-3}$	
Γ_{104}	$(\overline{K}^*(892) \pi)^- \nu_\tau \to \pi^- \overline{K}^0 \pi^0 \nu_\tau$		$(1.1 \pm 0.5) \times 10^{-3}$	
Γ_{105}	$K_1(1270)^- \nu_\tau$		$(4 \pm 4) \times 10^{-3}$	
Γ_{106}	$K_1(1400)^- \nu_\tau$		$(8 \pm 4) \times 10^{-3}$	
Γ_{107}	$K_2^*(1430)^- \nu_\tau$		$< 3 \times 10^{-3}$	CL=95%
Γ_{108}	$a_0(980)^- \geq 0$ neutrals ν_τ			
Γ_{109}	$\eta \pi^- \nu_\tau$		$< 1.4 \times 10^{-4}$	CL=95%
Γ_{110}	$\eta \pi^- \pi^0 \nu_\tau$	[a]	$(1.74 \pm 0.24) \times 10^{-3}$	

Γ_{111}	$\eta\pi^-\pi^0\pi^0\nu_\tau$		$(1.4 \pm 0.7) \times 10^{-4}$	
Γ_{112}	$\eta K^-\nu_\tau$		$(2.7 \pm 0.6) \times 10^{-4}$	
Γ_{113}	$\eta\pi^+\pi^-\pi^- \geq 0$ neutrals ν_τ		$< 3 \times 10^{-3}$	CL=90%
Γ_{114}	$\eta\pi^-\pi^+\pi^-\nu_\tau$		$(3.4 \pm 0.8) \times 10^{-4}$	
Γ_{115}	$\eta a_1(1260)^-\nu_\tau \to \eta\pi^-\rho^0\nu_\tau$		$< 3.9 \times 10^{-4}$	CL=90%
Γ_{116}	$\eta\eta\pi^-\nu_\tau$		$< 1.1 \times 10^{-4}$	CL=95%
Γ_{117}	$\eta\eta\pi^-\pi^0\nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%
Γ_{118}	$\eta'(958)\pi^-\nu_\tau$		$< 7.4 \times 10^{-5}$	CL=90%
Γ_{119}	$\eta'(958)\pi^-\pi^0\nu_\tau$		$< 8.0 \times 10^{-5}$	CL=90%
Γ_{120}	$\phi\pi^-\nu_\tau$		$< 2.0 \times 10^{-4}$	CL=90%
Γ_{121}	$\phi K^-\nu_\tau$		$< 6.7 \times 10^{-5}$	CL=90%
Γ_{122}	$f_1(1285)\pi^-\nu_\tau$		$(5.8 \pm 2.3) \times 10^{-4}$	
Γ_{123}	$f_1(1285)\pi^-\nu_\tau \to \eta\pi^-\pi^+\pi^-\nu_\tau$		$(1.9 \pm 0.7) \times 10^{-4}$	
Γ_{124}	$h^-\omega \geq 0$ neutrals ν_τ		(2.36 ± 0.08) %	
Γ_{125}	$h^-\omega\nu_\tau$	[a]	(1.93 ± 0.06) %	
Γ_{126}	$h^-\omega\pi^0\nu_\tau$	[a]	$(4.3 \pm 0.5) \times 10^{-3}$	
Γ_{127}	$h^-\omega 2\pi^0\nu_\tau$		$(1.9 \pm 0.8) \times 10^{-4}$	

Lepton Family number (*LF*), Lepton number (*L*), or Baryon number (*B*) violating modes (In the modes below, ℓ means a sum over *e* and μ modes)

L means lepton number violation (*e.g.* $\tau^- \to e^+\pi^-\pi^-$). Following common usage, *LF* means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \to e^-\pi^+\pi^-$). *B* means baryon number violation.

Γ_{128}	$e^-\gamma$	*LF*	$< 2.7 \times 10^{-6}$	CL=90%
Γ_{129}	$\mu^-\gamma$	*LF*	$< 3.0 \times 10^{-6}$	CL=90%
Γ_{130}	$e^-\pi^0$	*LF*	$< 3.7 \times 10^{-6}$	CL=90%
Γ_{131}	$\mu^-\pi^0$	*LF*	$< 4.0 \times 10^{-6}$	CL=90%
Γ_{132}	e^-K^0	*LF*	$< 1.3 \times 10^{-3}$	CL=90%
Γ_{133}	μ^-K^0	*LF*	$< 1.0 \times 10^{-3}$	CL=90%
Γ_{134}	$e^-\eta$	*LF*	$< 8.2 \times 10^{-6}$	CL=90%
Γ_{135}	$\mu^-\eta$	*LF*	$< 9.6 \times 10^{-6}$	CL=90%
Γ_{136}	$e^-\rho^0$	*LF*	$< 2.0 \times 10^{-6}$	CL=90%
Γ_{137}	$\mu^-\rho^0$	*LF*	$< 6.3 \times 10^{-6}$	CL=90%
Γ_{138}	$e^-K^*(892)^0$	*LF*	$< 5.1 \times 10^{-6}$	CL=90%
Γ_{139}	$\mu^-K^*(892)^0$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{140}	$e^-\overline{K}^*(892)^0$	*LF*	$< 7.4 \times 10^{-6}$	CL=90%
Γ_{141}	$\mu^-\overline{K}^*(892)^0$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{142}	$e^-\phi$	*LF*	$< 6.9 \times 10^{-6}$	CL=90%
Γ_{143}	$\mu^-\phi$	*LF*	$< 7.0 \times 10^{-6}$	CL=90%
Γ_{144}	$\pi^-\gamma$	*L*	$< 2.8 \times 10^{-4}$	CL=90%
Γ_{145}	$\pi^-\pi^0$	*L*	$< 3.7 \times 10^{-4}$	CL=90%
Γ_{146}	$e^-e^+e^-$	*LF*	$< 2.9 \times 10^{-6}$	CL=90%
Γ_{147}	$e^-\mu^+\mu^-$	*LF*	$< 1.8 \times 10^{-6}$	CL=90%
Γ_{148}	$e^+\mu^-\mu^-$	*LF*	$< 1.5 \times 10^{-6}$	CL=90%
Γ_{149}	$\mu^-e^+e^-$	*LF*	$< 1.7 \times 10^{-6}$	CL=90%
Γ_{150}	$\mu^+e^-e^-$	*LF*	$< 1.5 \times 10^{-6}$	CL=90%
Γ_{151}	$\mu^-\mu^+\mu^-$	*LF*	$< 1.9 \times 10^{-6}$	CL=90%
Γ_{152}	$e^-\pi^+\pi^-$	*LF*	$< 2.2 \times 10^{-6}$	CL=90%
Γ_{153}	$e^+\pi^-\pi^-$	*L*	$< 1.9 \times 10^{-6}$	CL=90%
Γ_{154}	$\mu^-\pi^+\pi^-$	*LF*	$< 8.2 \times 10^{-6}$	CL=90%
Γ_{155}	$\mu^+\pi^-\pi^-$	*L*	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{156}	$e^-\pi^+K^-$	*LF*	$< 6.4 \times 10^{-6}$	CL=90%
Γ_{157}	$e^-\pi^-K^+$	*LF*	$< 3.8 \times 10^{-6}$	CL=90%
Γ_{158}	$e^+\pi^-K^-$	*L*	$< 2.1 \times 10^{-6}$	CL=90%
Γ_{159}	$e^-K^+K^-$	*LF*	$< 6.0 \times 10^{-6}$	CL=90%
Γ_{160}	$e^+K^-K^-$	*L*	$< 3.8 \times 10^{-6}$	CL=90%
Γ_{161}	$\mu^-\pi^+K^-$	*LF*	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{162}	$\mu^-\pi^-K^+$	*LF*	$< 7.4 \times 10^{-6}$	CL=90%
Γ_{163}	$\mu^+\pi^-K^-$	*L*	$< 7.0 \times 10^{-6}$	CL=90%
Γ_{164}	$\mu^-K^+K^-$	*LF*	$< 1.5 \times 10^{-5}$	CL=90%
Γ_{165}	$\mu^+K^-K^-$	*L*	$< 6.0 \times 10^{-6}$	CL=90%
Γ_{166}	$e^-\pi^0\pi^0$	*LF*	$< 6.5 \times 10^{-6}$	CL=90%
Γ_{167}	$\mu^-\pi^0\pi^0$	*LF*	$< 1.4 \times 10^{-5}$	CL=90%
Γ_{168}	$e^-\eta\eta$	*LF*	$< 3.5 \times 10^{-5}$	CL=90%
Γ_{169}	$\mu^-\eta\eta$	*LF*	$< 6.0 \times 10^{-5}$	CL=90%
Γ_{170}	$e^-\pi^0\eta$	*LF*	$< 2.4 \times 10^{-5}$	CL=90%
Γ_{171}	$\mu^-\pi^0\eta$	*LF*	$< 2.2 \times 10^{-5}$	CL=90%
Γ_{172}	$\overline{p}\gamma$	*L,B*	$< 2.9 \times 10^{-4}$	CL=90%
Γ_{173}	$\overline{p}\pi^0$	*L,B*	$< 6.6 \times 10^{-4}$	CL=90%
Γ_{174}	$\overline{p}\eta$	*L,B*	$< 1.30 \times 10^{-3}$	CL=90%
Γ_{175}	e^- light boson	*LF*	$< 2.7 \times 10^{-3}$	CL=95%
Γ_{176}	μ^- light boson	*LF*	$< 5 \times 10^{-3}$	CL=95%

[*a*] Basis mode for the τ.

[*b*] See the Particle Listings below for the energy limits used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 65 branching ratios uses 141 measurements and one constraint to determine 29 parameters. The overall fit has a $\chi^2 = 94.2$ for 113 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_5	11									
x_9	−11	−10								
x_{10}	0	0	−34							
x_{13}	−15	−13	−17	3						
x_{15}	0	0	2	−7	−37					
x_{19}	−16	−14	−15	1	−24	1				
x_{20}	0	0	1	−3	1	−4	−18			
x_{23}	−7	−6	−13	14	−14	17	−14	8		
x_{24}	0	0	7	−19	9	−23	2	−11	−72	
x_{26}	−5	−4	−5	0	−7	0	−9	0	−4	0
x_{32}	−2	−2	−24	0	−3	0	−12	0	−2	1
x_{34}	0	0	−4	−3	1	−3	−2	−2	7	−9
x_{36}	−2	−2	−1	1	−4	1	−3	1	−8	3
x_{38}	−1	−1	1	−3	0	−4	−1	−2	6	−11
x_{41}	−1	−1	−3	0	−2	0	−2	0	−1	0
x_{57}	−7	−6	−4	0	−10	0	−9	0	−4	0
x_{65}	−3	−3	−4	0	−5	0	−5	0	−1	−1
x_{73}	−1	−1	−2	0	−2	0	−2	0	−1	0
x_{74}	−6	−5	−7	0	−9	0	−9	0	−4	0
x_{79}	0	0	1	0	0	1	0	0	−1	2
x_{81}	0	0	0	1	0	1	0	0	−1	3
x_{84}	0	0	0	0	0	0	0	0	0	0
x_{85}	0	0	0	0	0	0	0	0	0	0
x_{92}	0	0	−1	0	−1	0	−1	0	0	0
x_{93}	0	0	0	0	0	0	0	0	0	0
x_{110}	−1	−1	−1	0	−1	0	−1	0	−1	0
x_{125}	−2	−2	−3	0	−3	0	−4	0	−1	0
x_{126}	−2	−2	−3	0	−3	0	−4	0	−2	0
	x_3	x_5	x_9	x_{10}	x_{13}	x_{15}	x_{19}	x_{20}	x_{23}	x_{24}

x_{32}	−1									
x_{34}	0	−10								
x_{36}	−1	−8	−1							
x_{38}	0	−3	−2	−29						
x_{41}	−1	−4	−1	−2	−1					
x_{57}	−3	−17	4	0	0	0				
x_{65}	−2	1	0	−10	7	0	−10			
x_{73}	1	0	0	0	0	0	−1	−2		
x_{74}	−3	0	0	0	0	−1	−13	−15	−3	
x_{79}	0	2	−18	0	0	0	−40	3	0	0
x_{81}	0	1	1	7	−23	0	3	−41	0	0
x_{84}	0	0	0	0	0	0	−23	3	0	0
x_{85}	0	0	0	0	0	0	2	−30	0	0
x_{92}	0	0	0	0	0	0	0	0	0	0
x_{93}	0	0	0	0	0	0	0	0	0	0
x_{110}	−14	0	0	0	0	0	−1	0	−14	−1
x_{125}	−1	0	0	−4	−1	0	−6	−28	−1	−8
x_{126}	−1	0	0	0	0	0	−1	−4	−42	−4
	x_{26}	x_{32}	x_{34}	x_{36}	x_{38}	x_{41}	x_{57}	x_{65}	x_{73}	x_{74}

	x_{79}	x_{81}	x_{84}	x_{85}	x_{92}	x_{93}	x_{110}	x_{125}
x_{81}	−8							
x_{84}	0	0						
x_{85}	0	0	−9					
x_{92}	0	0	0	0				
x_{93}	0	0	0	0	−24			
x_{110}	0	0	0	0	0	0		
x_{125}	0	0	0	0	0	0	0	
x_{126}	0	0	0	0	0	0	0	−1

τ BRANCHING FRACTIONS

Revised April 1998 by K.G. Hayes (Hillsdale College).

For the last six years, the rate of publication of new experimental results on the τ lepton has been high. The 30 new experimental papers listed in the τ References for this edition have produced significant changes in the τ Listings. The new results are made possible by the large τ data sets accumulated by the LEP experiments and by CLEO. Measurements of new τ-decay modes with small ($< 10^{-3}$) branching fractions have been published, and stringent upper limits on other new allowed τ decays have also been published. Significant improvements in branching fraction upper limits for forbidden τ decays have been made including the determination of upper limits for 12 new forbidden decay modes. The great majority of branching fraction upper limits for forbidden modes are now in the range of 10^{-5} to 10^{-6}.

Relatively precise branching fractions for 3-prong exclusive τ-decay modes containing charged kaons have finally been published [1]. This allows the determination of branching fractions for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$, the last exclusive τ-decay modes with large branching fractions to be measured. The new measurements have resulted in a 30% increase in the number of τ-decay modes in the Listings; 176 decay modes are listed in the current edition, although many are not mutually independent.

There have also been many new measurements of τ-decay parameters. For most parameters, the uncertainty on the world average has decreased by a factor of 2.5 or more. Finally, new experimental limits have been published for the various τ-dipole moments. However, there have been few new measurements of τ-decay modes with large branching fractions, and the world average values for most of these branching fractions have changed little since the last edition.

The constrained fit to τ branching fractions: The Lepton Summary Table and the List of τ-Decay Modes contain branching fractions for 105 conventional τ-decay modes and upper limits on the branching fractions for 22 other conventional τ-decay modes. Of the 105 modes with branching fractions, 76 are derived from a constrained fit to τ branching fraction data. The goal of the constrained fit is to make optimal use of the experimental data to determine τ branching fractions. For example, the new branching fractions for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ are determined mostly from experimental measurements of the branching fractions for modes $\tau^- \to h^-h^-h^+\nu_\tau$ and $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ and the new measurements of exclusive branching fractions for 3-prong modes containing charged kaons and 0 or 1 π^0's.

Branching fractions from the constrained fit are derived from a set of basis modes. The basis modes form an exclusive set whose branching fractions are constrained to sum exactly to one. The list of 29 basis modes selected for the 1998 fit are listed in Table 1. The only change for the 1996 basis set is that the two modes $\tau \to h^-h^-h^+\nu_\tau$ (ex. K^0,ω) and $\tau \to h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0,ω) have been replaced by the six new modes:

$\tau \to \pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0,ω),
$\tau \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0,ω),
$\tau \to K^-\pi^+\pi^-\nu_\tau$ (ex. K^0),
$\tau \to K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0),
$\tau \to K^-K^+\pi^-\nu_\tau$, and
$\tau \to K^-K^+\pi^-\pi^0\nu_\tau$.

Table 1: Basis modes for the 1998 fit to τ branching fraction data.

$e^-\overline{\nu}_e\nu_\tau$	$K^-K^0\nu_\tau$
$\mu^-\overline{\nu}_\mu\nu_\tau$	$K^-K^0\pi^0\nu_\tau$
$\pi^-\nu_\tau$	$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0,ω)
$\pi^-\pi^0\nu_\tau$	$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0,ω)
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	$K^-\pi^+\pi^-\nu_\tau$ (ex. K^0)
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0)
$h^-4\pi^0\nu_\tau$ (ex. K^0)	$K^-K^+\pi^-\nu_\tau$
$K^-\nu_\tau$	$K^-K^+\pi^-\pi^0\nu_\tau$
$K^-\pi^0\nu_\tau$	$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0,ω,η)
$K^-2\pi^0\nu_\tau$ (ex. K^0)	$h^-h^-h^+ \geq 3\pi^0\nu_\tau$
$K^-3\pi^0\nu_\tau$ (ex. K^0)	$3h^-2h^+\nu_\tau$ (ex. K^0)
$\pi^-\overline{K}^0\nu_\tau$	$3h^-2h^+\pi^0\nu_\tau$ (ex. K^0)
$\pi^-\overline{K}^0\pi^0\nu_\tau$	$h^-\omega\nu_\tau$
$\pi^-K^0\overline{K}^0\nu_\tau$	$h^-\omega\pi^0\nu_\tau$
	$\pi^-\eta\pi^0\nu_\tau$

In selecting the basis modes, assumptions and choices must be made. Factors pertaining to the selection of the 1996 basis modes are described in the 1996 edition. Additional assumptions have been made in selecting the six new modes for the 1998 basis set. We assume the decays $\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau$ and $\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu_\tau$ have negligible branching fractions. This is consistent with Standard Model predictions for τ decay, although the experimental limits for these branching fractions are not very stringent. The 95% CL upper limits for these branching fractions in the current Listings are $\mathrm{B}(\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau) < 0.25\%$ and $\mathrm{B}(\pi^+K^-K^- \geq 0\pi^0\nu_\tau) < 0.09\%$, values not so different from measured branching fractions for allowed 3-prong modes containing charged kaons. Although our usual goal is to impose as few theoretical constraints as possible so that the world averages and fit results can be used to test the theoretical constraints (*i.e.*, we do not make use of the theoretical constraint from lepton universality on the ratio of the τ-leptonic branching fractions $B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)/B(\tau^- \to e^- \overline{\nu}_e \nu_\tau) = 0.9728$), the experimental challenge to identify charged prongs in 3-prong τ decays is sufficiently difficult that experimenters have been forced to make these assumptions when measuring the branching fractions of the allowed decays.

We also assume the branching fraction for the allowed decay $\tau^- \to K^- K^+ K^- \geq 0\pi^0 \nu_\tau$ is negligible. This decay has limited phase space, and the branching fraction is expected to be very small. The branching fraction upper limit for this decay in the current Listings is $B(\tau^- \to K^- K^+ K^- \geq 0\pi^0 \nu_\tau) < 0.21\%$ at 95% CL, and the ALEPH Collaboration [1] has determined a much more stringent limit on the branching fraction $B(\tau^- \to K^- K^+ K^- \nu_\tau) < 0.019\%$ at 90% CL.

Recent measurements of several new decay modes having very small branching fractions have raised two other issues regarding the choice of basis modes. The ALEPH Collaboration has recently measured new branching fractions for 1-prong τ decays containing two neutral kaons [2]. The basis set has just one τ-decay mode containing two neutral kaons: $\tau^- \to \pi^- K^0 \overline{K}^0 \nu_\tau$. In calculating the contribution of this decay to other measured τ-decay modes, we assume the two neutral kaons decay independently:

$$\begin{aligned} B(\tau^- \to \pi^- K^0_S K^0_S \nu_\tau) &= B(\tau^- \to \pi^- K^0_L K^0_L \nu_\tau) \\ &= \tfrac{1}{4} B(\pi^- K^0 \overline{K}^0 \nu_\tau). \\ B(\tau^- \to \pi^- K^0_S K^0_L \nu_\tau) &= \tfrac{1}{2} B(\pi^- K^0 \overline{K}^0 \nu_\tau). \end{aligned}$$

This assumption may be incorrect. For example, Bose-Einstein correlations between the two neutral kaons can in principle alter these branching fractions. The ratio of the ALEPH measurement of B $(\tau^- \to \pi^- K^0_S K^0_L \nu_\tau) = (0.101 \pm 0.023 \pm 0.013)\%$ to the average of the CLEO [3] and ALEPH [2] measurements of $B(\tau^- \to \pi^- K^0_S K^0_S \nu_\tau) = (0.024 \pm 0.005)\%$ is not inconsistent with our assumed value for this ratio of 2. For the sake of simplicity, we retain in this edition the assumption of independent K^0 decay.

There are several newly measured modes with small branching fractions [4] which cannot be expressed in terms of the selected basis modes and are therefore left out of the fit:

$B(K^0 h^+ h^- h^- \nu_\tau) = (2.3 \pm 2.0) \times 10^{-4}$,
$B(\pi^- K^0_S K^0_L \pi^0 \nu_\tau) = (3.1 \pm 1.2) \times 10^{-4}$,
$B(\tau^- \to \pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau) = (6 \pm 4) \times 10^{-4}$,

plus the $\eta \to \gamma\gamma$ component of the branching fractions

$B(\eta \pi^- \pi^+ \pi^- \nu_\tau) = (3.4 \pm 0.8) \times 10^{-4}$,
$B(\eta \pi^- \pi^0 \pi^0 \nu_\tau) = (1.4 \pm 0.7) \times 10^{-4}$, and
$B(\eta K^- \nu_\tau) = (2.7 \pm 0.6) \times 10^{-4}$.

The sum of these excluded branching fractions is $(0.15 \pm 0.05)\%$. This is near our goal of 0.1% for the internal consistency of the τ Listings for this edition, and thus for simplicity we do not include these small branching fraction decay modes in the basis set.

The only significant difference between the world average value and the constrained fit value for branching fractions in the 1996 edition was for the 1-prong and 3-prong topological branching fractions. The average values for the topological branching fractions were dominated by old measurements from the pre-LEP era. Some of these old experiments had significantly underestimated their experimental uncertainties, with the result that, in the period between 1986 and 1990, the uncertainty in the world averages for the 1-prong and 3-prong topological branching fractions were considerably smaller than the uncertainty in the world averages of the very well-measured leptonic branching fractions [5]. Also, several of these old topological branching fraction measurements made the largest contributions the the constrained χ^2 fit. These measurement are now very old and have been retired.

The constrained fit has a χ^2 of 94 for 113 degrees of freedom. The only basis mode branching fraction which shifted more than 1σ from its 1996 value is $B(\tau^- \to \pi^- \nu_\tau)$ which changed from $(11.31 \pm 0.15)\%$ to $(11.08 \pm 0.11)\%$ due mainly to the new measurement of $B(\tau^- \to h^- \nu_\tau)$ by the CLEO Collaboration [6]. The fit and average values for the topological branching fractions are consistent. Table 2 compares the current fit and average values for

$B_1 \equiv B(\text{particle}^- \geq 0 \text{ neutrals } \geq 0 K^0_L \nu_\tau)$ and
$B_3 \equiv B(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau)$

with the values from the 1996 edition.

Table 2: Fit and average values for B_1 and B_3.

Branching fraction		1996 Fit	1998 Fit
B_1	Fit:	84.96 ± 0.17	84.71 ± 0.13
B_1	Ave:	85.91 ± 0.30	85.1 ± 0.4
B_3	Fit:	14.92 ± 0.17	15.18 ± 0.13
B_3	Ave:	14.01 ± 0.29	14.8 ± 0.4

Another measure of the overall consistency of the τ branching fraction data with the fit constraint is a comparison of the fit and average values for the leptonic branching fractions. Table 3 compares the current fit and average values for $B_e \equiv B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)$ and $B_\mu \equiv B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)$ with the values from the 1996 edition.

Table 3: Fit and average values for $\tau^- \to e^- \overline{\nu}_e \nu_\tau$ and $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$.

Branching fraction		1996 Fit	1998 Fit
B_e	Fit:	17.83 ± 0.08	17.81 ± 0.07
B_e	Ave:	17.80 ± 0.08	17.78 ± 0.08
B_μ	Fit:	17.35 ± 0.10	17.37 ± 0.09
B_μ	Ave:	17.30 ± 0.10	17.32 ± 0.09

Conclusions: Many new measurements of τ-lepton properties have been made in the last two years. Experimenters have exploited the availability of large data sets to measure τ-decay modes with either small branching fractions or low detection efficiencies. Charged particle identification in 3-prong decays has finally allowed the experimental determination of the branching fraction for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$, the last exclusive τ-decay modes with large branching fractions to be measured. The basis set of τ-decay modes used in the constrained fit to branching fractions has been expanded to include the new measurements of exclusive 3-prong decays with identified charged prongs and 0 or 1 π^0's. There is no significant evidence of any inconsistency in the branching fraction data used in the constrained fit or to calculate world average values.

References

1. ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. **C1**, 65 (1998).
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3. CLEO Collaboration, T.E. Coan *et al.*, Phys. Rev. **D53**, 6037 (1996).
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6. CLEO Collaboration, A. Anastassov *et al.*, Phys. Rev. **D55**, 2559 (1997).

τ^- BRANCHING RATIOS

$\Gamma(\text{particle}^- \geq 0\ \text{neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))/\Gamma_{\text{total}}$ Γ_1/Γ

$\Gamma_1/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{36}+0.6569\Gamma_{38}+0.4316\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})/\Gamma$

The charged particle here can be e, μ, or hadron. In many analyses, the sum of the topological branching fractions (1, 3, and 5 prongs) is constrained to be unity. Since the 5-prong fraction is very small, the measured 1-prong and 3-prong fractions are highly correlated and cannot be treated as independent quantities in our overall fit. We arbitrarily choose to use the 3-prong fraction in our fit, and leave the 1-prong fraction out. We do, however, use these 1-prong measurements in our average below. The measurements used only for the average are marked "avg," whereas "f&a" marks a result used for the fit and the average.

VALUE (%)		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
84.71±0.13 OUR FIT	Error includes scale factor of 1.2.				
85.1 ±0.4 OUR AVERAGE					
85.6 ±0.6 ±0.3	avg	3300	[19] ADEVA 91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
84.9 ±0.4 ±0.3	avg		BEHREND 89B	CELL	E^{ee}_{cm}= 14–47 GeV
84.7 ±0.8 ±0.6	avg		[20] AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
86.4 ±0.3 ±0.3			ABACHI 89B	HRS	E^{ee}_{cm}= 29 GeV
87.1 ±1.0 ±0.7			[21] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
87.2 ±0.5 ±0.8			SCHMIDKE 86	MRK2	E^{ee}_{cm}= 29 GeV
84.7 ±1.1 $^{+1.6}_{-1.3}$		169	[22] ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
86.1 ±0.5 ±0.9			BARTEL 85F	JADE	E^{ee}_{cm}= 34.6 GeV
87.8 ±1.3 ±3.9			[23] BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
86.7 ±0.3 ±0.6			FERNANDEZ 85	MAC	E^{ee}_{cm}= 29 GeV

[19] Not independent of ADEVA 91F $\Gamma(h^- h^- h^+ \geq 0\text{neut.}\ \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$ value.

[20] Not independent of AIHARA 87B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, and $\Gamma(h^- \geq 0\ \text{neutrals} \geq 0K^0_L\ \nu_\tau)/\Gamma_{\text{total}}$ values.

[21] Not independent of SCHMIDKE 86 value (also not independent of BURCHAT 87 value for $\Gamma(h^- h^- h^+ \geq 0\text{neut.}\ \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$.

[22] Not independent of ALTHOFF 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(h^- \geq 0\ \text{neutrals} \geq 0K^0_L\ \nu_\tau)/\Gamma_{\text{total}}$, and $\Gamma(h^- h^- h^+ \geq 0\text{neut.}\ \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$ values.

[23] Not independent of (1-prong + $0\pi^0$) and (1-prong + $\geq 1\pi^0$) values.

$\Gamma(\text{particle}^- \geq 0\ \text{neutrals} \geq 0K^0\nu_\tau)/\Gamma_{\text{total}}$ Γ_2/Γ

$\Gamma_2/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+\Gamma_{32}+\Gamma_{34}+\Gamma_{36}+\Gamma_{38}+\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})/\Gamma$

VALUE (%)		*DOCUMENT ID*	*TECN*	*COMMENT*
85.30±0.13 OUR FIT	Error includes scale factor of 1.2.			
84.59±0.33 OUR AVERAGE				
84.48±0.27±0.23	avg	ACTON 92H	OPAL	1990–1991 LEP runs
85.45 $^{+0.69}_{-0.73}$ ±0.65	f&a	DECAMP 92C	ALEP	1989–1990 LEP runs

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$ Γ_3/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
17.37±0.09 OUR FIT					
17.32±0.09 OUR AVERAGE					
17.37±0.08±0.18	avg		[24] ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV
17.31±0.11±0.05	f&a	20.7k	BUSKULIC 96C	ALEP	1991–1993 LEP runs
17.02±0.19±0.24	f&a	6586	ABREU 95T	DLPH	1991–1992 LEP runs
17.36±0.27	f&a	7941	AKERS 95I	OPAL	1990–1992 LEP runs
17.6 ±0.4 ±0.4	f&a	2148	ADRIANI 93M	L3	E^{ee}_{cm}= 88–94 GeV
17.4 ±0.3 ±0.5	avg		[25] ALBRECHT 93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
17.35±0.41±0.37	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
17.7 ±0.8 ±0.4	f&a	568	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
17.4 ±1.0	f&a	2197	ADEVA 88	MRKJ	E^{ee}_{cm}= 14–16 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
17.7 ±1.2 ±0.7			AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
18.3 ±0.9 ±0.8			BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
18.6 ±0.8 ±0.7		558	[26] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
12.9 ±1.7 $^{+0.7}_{-0.5}$			ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
18.0 ±0.9 ±0.5		473	[26] ASH 85B	MAC	E^{ee}_{cm}= 29 GeV
18.0 ±1.0 ±0.6			[27] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
19.4 ±1.6 ±1.7		153	BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
17.6 ±2.6 ±2.1		47	BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV
17.8 ±2.0 ±1.8			BERGER 81B	PLUT	E^{ee}_{cm}= 9–32 GeV

[24] This ANASTASSOV 97 result is not independent of $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$ values.

[25] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and ALBRECHT 93G $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{\text{total}}$ values.

[26] Modified using $B(e^-\overline{\nu}_e\nu_\tau)$/B("1 prong") and B("1 prong") = 0.855.

[27] Error correlated with BALTRUSAITIS 85 $e\nu\overline{\nu}$ value.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(\text{particle}^- \geq 0\ \text{neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))$ Γ_3/Γ_1

$\Gamma_3/\Gamma_1 = \Gamma_3/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{36}+0.6569\Gamma_{38}+0.4316\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.2051±0.0010 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.217 ±0.009 ±0.008		BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
0.211 ±0.010 ±0.006	390	ASH 85B	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.30±0.04±0.05	116	[28] ALEXANDER 96S	OPAL	1991–1994 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.23±0.10	10	[29] WU 90	MRK2	E^{ee}_{cm}= 29 GeV

[28] ALEXANDER 96S impose requirements on detected γ's corresponding to a τ-rest-frame energy cutoff E_γ >20 MeV.

[29] WU 90 reports $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) = 0.013 \pm 0.006$, which is converted to $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{\text{total}}$ using $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{\text{total}} = 17.35\%$. Requirements on detected γ's correspond to a τ rest frame energy cutoff E_γ > 37 MeV.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$ Γ_5/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)		*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
17.81±0.07 OUR FIT					
17.78±0.08 OUR AVERAGE					
17.76±0.06±0.17	f&a		ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV
17.78±0.10±0.09	f&a	25.3k	ALEXANDER 96D	OPAL	1991–1994 LEP runs
17.79±0.12±0.06	f&a	20.6k	BUSKULIC 96C	ALEP	1991–1993 LEP runs
17.51±0.23±0.31	f&a	5059	ABREU 95T	DLPH	1991–1992 LEP runs
17.9 ±0.4 ±0.4	f&a	2892	ADRIANI 93M	L3	E^{ee}_{cm}= 88–94 GeV

17.5 ±0.3 ±0.5	avg		[30] ALBRECHT 93G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
19.1 ±0.4 ±0.6	avg	2960	[31] AMMAR 92	CLEO	$E^{ee}_{\rm cm}$= 10.5–10.9 GeV
18.09±0.45±0.45	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
17.0 ±0.5 ±0.6	f&a	1.7k	ABACHI 90	HRS	$E^{ee}_{\rm cm}$= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
17.97±0.14±0.23		3970	AKERIB 92	CLEO	Repl. by ANASTASSOV 97
18.4 ±0.8 ±0.4		644	BEHREND 90	CELL	$E^{ee}_{\rm cm}$= 35 GeV
16.3 ±0.3 ±3.2			JANSSEN 89	CBAL	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
18.4 ±1.2 ±1.0			AIHARA 87B	TPC	$E^{ee}_{\rm cm}$= 29 GeV
19.1 ±0.8 ±1.1			BURCHAT 87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
16.8 ±0.7 ±0.9		515	[31] BARTEL 86D	JADE	$E^{ee}_{\rm cm}$= 34.6 GeV
$20.4 \pm 3.0 {}^{+1.4}_{-0.9}$			ALTHOFF 85	TASS	$E^{ee}_{\rm cm}$= 34.5 GeV
17.8 ±0.9 ±0.6		390	[31] ASH 85B	MAC	$E^{ee}_{\rm cm}$= 29 GeV
18.2 ±0.7 ±0.5			[32] BALTRUSAIT...85	MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV
13.0 ±1.9 ±2.9			BERGER 85	PLUT	$E^{ee}_{\rm cm}$= 34.6 GeV
18.3 ±2.4 ±1.9		60	BEHREND 83C	CELL	$E^{ee}_{\rm cm}$= 34 GeV
16.0 ±1.3		459	[33] BACINO 78B	DLCO	$E^{ee}_{\rm cm}$= 3.1–7.4 GeV

[30] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and ALBRECHT 93G $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{\rm total}$ values.

[31] Modified using $B(e^-\overline{\nu}_e\nu_\tau)$/B("1 prong") and B("1 prong") ,= 0.855.

[32] Error correlated with BALTRUSAITIS 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\rm total}$.

[33] BACINO 78B value comes from fit to events with $e^\pm$ and one other nonelectron charged prong.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma(\text{particle}^- \geq 0\ \text{neutrals} \geq 0K^0_L\nu_\tau\ (\text{"1-prong"}))$ Γ_5/Γ_1

$\Gamma_5/\Gamma_1 = \Gamma_5/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{36}+0.6569\Gamma_{38}+0.4316\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.2102±0.0009 OUR FIT	Error includes scale factor of 1.1.			
0.2231±0.0044±0.0073	2856	AMMAR 92	CLEO	$E^{ee}_{\rm cm}$= 10.5–10.9 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.196 ±0.008 ±0.010		BARTEL 86D	JADE	$E^{ee}_{\rm cm}$= 34.6 GeV
0.208 ±0.010 ±0.007	390	ASH 85B	MAC	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{\rm total}$ $\Gamma_3\Gamma_5/\Gamma^2$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03094±0.00021 OUR FIT	Error includes scale factor of 1.1.			
0.0306 ±0.0005 ±0.0013	3230	ALBRECHT 93G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0288 ±0.0017 ±0.0019		ASH 85B	MAC	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ Γ_3/Γ_5

Predicted to be 1 for sequential lepton, 1/2 for para-electron, and 2 for para-muon. Para-electron also ruled out by HEILE 78.

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		DOCUMENT ID	TECN	COMMENT
0.976 ±0.006 OUR FIT				
0.978 ±0.011 OUR AVERAGE				
0.9777±0.0063±0.0087	f&a	ANASTASSOV 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.997 ±0.035 ±0.040	f&a	ALBRECHT 92D	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

$\Gamma(h^- \geq 0\ \text{neutrals} \geq 0K^0_L\,\nu_\tau)/\Gamma_{\rm total}$ Γ_6/Γ

$\Gamma_6/\Gamma = (\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{36}+0.6569\Gamma_{38}+0.4316\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})/\Gamma$

VALUE (%)		DOCUMENT ID	TECN	COMMENT
49.52±0.16 OUR FIT	Error includes scale factor of 1.2.			
48.6 ±1.2 ±0.9	**avg**	[34] AIHARA 87B	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[34] Not independent of AIHARA 87B $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^+2\pi^-(\geq 0\pi^0)\nu$ values.

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma_{\rm total}$ Γ_7/Γ

$\Gamma_7/\Gamma = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{32}+\frac{1}{2}\Gamma_{34}+\frac{1}{4}\Gamma_{41})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
12.32±0.12 OUR FIT	Error includes scale factor of 1.5.				
12.42±0.14 OUR AVERAGE					
12.44±0.11±0.11	f&a	15k	[35] BUSKULIC 96	ALEP	1991–1993 LEP run
12.47±0.26±0.43	f&a	2967	[36] ACCIARRI 95	L3	1992 LEP run
12.4 ±0.7 ±0.7	f&a	283	[37] ABREU 92N	DLPH	1990 LEP run
11.7 ±0.6 ±0.8	avg		[38] ALBRECHT 92D	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
12.98±0.44±0.33	f&a		[39] DECAMP 92C	ALEP	1989–1990 LEP runs
12.1 ±0.7 ±0.5	f&a	309	ALEXANDER 91D	OPAL	1990 LEP run
12.3 ±0.9 ±0.5	f&a	1338	BEHREND 90	CELL	$E^{ee}_{\rm cm}$= 35 GeV
11.3 ±0.5 ±0.8	avg	798	[40] FORD 87	MAC	$E^{ee}_{\rm cm}$= 29 GeV
12.3 ±0.6 ±1.1	avg	328	[41] BARTEL 86D	JADE	$E^{ee}_{\rm cm}$= 34.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11.1 ±1.1 ±1.4			[42] BURCHAT 87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
13.0 ±2.0 ±4.0			BERGER 85	PLUT	$E^{ee}_{\rm cm}$= 34.6 GeV
11.2 ±1.7 ±1.2		34	[43] BEHREND 83C	CELL	$E^{ee}_{\rm cm}$= 34 GeV

[35] BUSKULIC 96 quote 11.78 ± 0.11 ± 0.13 We add 0.66 to undo their correction for unseen K^0_L and modify the systematic error accordingly.

[36] ACCIARRI 95 with 0.65% added to remove their correction for $\pi^- K^0_L$ backgrounds.

[37] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.

[38] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$, $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)$, and $\Gamma(h^- \geq 0K^0_L\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ values.

[39] DECAMP 92C quote $B(h^- \geq 0K^0_L \geq 0\,(K^0_S \rightarrow \pi^+\pi^-)\,\nu_\tau) = 13.32 \pm 0.44 \pm 0.33$. We subtract 0.35 to correct for their inclusion of the K^0_S decays.

[40] FORD 87 result for $B(\pi^-\nu_\tau)$ with 0.67% added to remove their K^- correction and adjusted for 1992 B("1 prong").

[41] BARTEL 86D result for $B(\pi^-\nu_\tau)$ with 0.59% added to remove their K^- correction and adjusted for 1992 B("1 prong").

[42] BURCHAT 87 with 1.1% added to remove their correction for K^- and $K^*(892)^-$ backgrounds.

[43] BEHREND 83C quote $B(\pi^-\nu_\tau) = 9.9 \pm 1.7 \pm 1.3$ after subtracting 1.3 ± 0.5 to correct for $B(K^-\nu_\tau)$.

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma(\text{particle}^- \geq 0\ \text{neutrals} \geq 0K^0_L\nu_\tau\ (\text{"1-prong"}))$ Γ_7/Γ_1

$\Gamma_7/\Gamma_1 = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{32}+\frac{1}{2}\Gamma_{34}+\frac{1}{4}\Gamma_{41})/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{36}+0.6569\Gamma_{38}+0.4316\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1455±0.0014 OUR FIT	Error includes scale factor of 1.4.			
0.135 ±0.009 OUR AVERAGE				
0.131 ±0.006 ±0.009	798	[44] FORD 87	MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.143 ±0.007 ±0.013	328	[45] BARTEL 86D	JADE	$E^{ee}_{\rm cm}$= 34.6 GeV

[44] FORD 87 result divided by 0.865, their assumed value for B("1 prong").

[45] BARTEL 86D result with 0.6% added to remove their K^- correction and then divided by 0.866, their assumed value for B("1 prong").

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ Γ_7/Γ_5

$\Gamma_7/\Gamma_5 = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{32}+\frac{1}{2}\Gamma_{34}+\frac{1}{4}\Gamma_{41})/\Gamma_5$

VALUE	DOCUMENT ID	TECN	COMMENT
0.692±0.008 OUR FIT	Error includes scale factor of 1.4.		
0.678±0.037±0.044	ALBRECHT 92D	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.647±0.039±0.061	[46] BARTEL 86D	JADE	$E^{ee}_{\rm cm}$= 34.6 GeV

[46] Combined result of BARTEL 86D $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^-\nu$ assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu})$ = 0.973.

$\Gamma(h^-\nu_\tau)/\Gamma_{\rm total}$ $\Gamma_8/\Gamma = (\Gamma_9+\Gamma_{10})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID	TECN	COMMENT
11.79±0.12 OUR FIT	Error includes scale factor of 1.5.			
11.65±0.21 OUR AVERAGE	Error includes scale factor of 1.9.			
11.98±0.13±0.16	f&a	ACKERSTAFF 98M	OPAL	1991–1995 LEP runs
11.52±0.05±0.12	f&a	ANASTASSOV 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(h^-\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ $\Gamma_8/\Gamma_5 = (\Gamma_9+\Gamma_{10})/\Gamma_5$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		DOCUMENT ID	TECN	COMMENT
0.662 ±0.008 OUR FIT	Error includes scale factor of 1.4.			
0.6484±0.0041±0.0060	**avg**	[47] ANASTASSOV 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

[47] Not independent of ANASTASSOV 97 $\Gamma(h^-\nu_\tau)/\Gamma_{\rm total}$ value.

$\Gamma(\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_9/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
11.08±0.13 OUR FIT	Error includes scale factor of 1.4.				
11.07±0.18 OUR AVERAGE					
11.06±0.11±0.14	avg		[48] BUSKULIC 96	ALEP	LEP 1991–1993 data
11.7 ±0.4 ±1.8	f&a	1138	BLOCKER 82D	MRK2	$E^{ee}_{\rm cm}$= 3.5–6.7 GeV

[48] Not independent of BUSKULIC 96 $B(h^-\nu_\tau)$ and $B(K^-\nu_\tau)$ values.

$\Gamma(K^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{10}/Γ

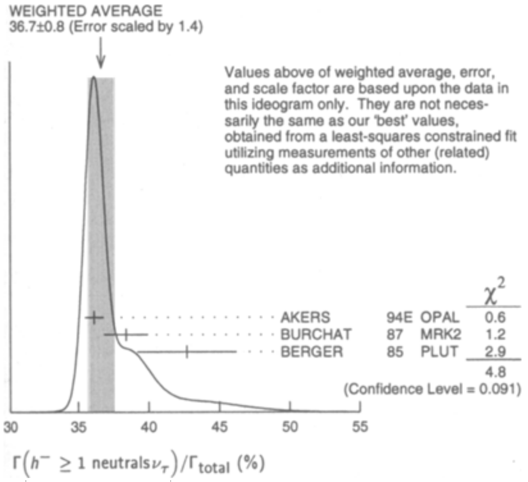
VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.71±0.05 OUR FIT					
0.71±0.05 OUR AVERAGE					
0.72±0.04±0.04	728	BUSKULIC	96	ALEP	LEP 1991–1993 data
0.85±0.18	27	ABREU	94K	DLPH	LEP 1992 Z data
0.66±0.07±0.09	99	BATTLE	94	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
0.59±0.18	16	MILLS	84	DLCO	$E^{ee}_{\rm cm}$ = 29 GeV
1.3 ±0.5	15	BLOCKER	82B	MRK2	$E^{ee}_{\rm cm}$ = 3.9–6.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.64±0.05±0.05	336	BUSKULIC	94E	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- \geq 1\,{\rm neutrals}\,\nu_\tau)/\Gamma_{\rm total}$ Γ_{11}/Γ

$\Gamma_{11}/\Gamma = (\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{32}+0.157\Gamma_{34}+0.157\Gamma_{36}+0.157\Gamma_{38}+0.0246\Gamma_{41}+0.708\Gamma_{110}+0.09\Gamma_{125}+0.09\Gamma_{126})/\Gamma$

VALUE (%)	DOCUMENT ID		TECN	COMMENT
36.91±0.17 OUR FIT	Error includes scale factor of 1.2.			
36.7 ±0.8 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
36.14±0.33±0.58	AKERS	94E	OPAL	1991–1992 LEP runs
38.4 ±1.2 ±1.0	[49] BURCHAT	87	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
42.7 ±2.0 ±2.9	BERGER	85	PLUT	$E^{ee}_{\rm cm}$ = 34.6 GeV

[49] BURCHAT 87 quote for B($\pi^\pm \geq 1$ neutral ν_τ) = 0.378 ± 0.012 ± 0.010. We add 0.006 to account for contribution from ($K^{*-}\nu_\tau$) which they fixed at BR = 0.013.


WEIGHTED AVERAGE
36.7±0.8 (Error scaled by 1.4)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(h^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ $\Gamma_{12}/\Gamma = (\Gamma_{13}+\Gamma_{15})/\Gamma$

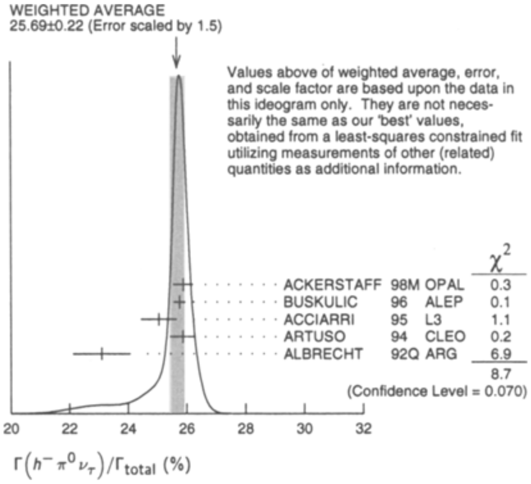
VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
25.84±0.14 OUR FIT	Error includes scale factor of 1.1.				
25.69±0.22 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
25.89±0.17±0.29		ACKERSTAFF	98M	OPAL	1991–1995 LEP runs
25.76±0.15±0.13	31k	BUSKULIC	96	ALEP	LEP 1991–1993 data
25.05±0.35±0.50	6613	ACCIARRI	95	L3	1992 LEP run
25.87±0.12±0.42	51k	[50] ARTUSO	94	CLEO	$E^{ee}_{\rm cm}$ = 10.6 GeV
23.1 ±0.4 ±0.9	1249	[51] ALBRECHT	92Q	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
25.98±0.36±0.52		[52] AKERS	94E	OPAL	Repl. by ACKERSTAFF 98M
22.9 ±0.8 ±1.3	283	[53] ABREU	92N	DLPH	$E^{ee}_{\rm cm}$ = 88.2–94.2 GeV
25.02±0.64±0.88	1849	DECAMP	92C	ALEP	1989–1990 LEP runs
22.0 ±0.8 ±1.9	779	ANTREASYAN	91	CBAL	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV
22.6 ±1.5 ±0.7	1101	BEHREND	90	CELL	$E^{ee}_{\rm cm}$ = 35 GeV
23.1 ±1.9 ±1.6		BEHREND	84	CELL	$E^{ee}_{\rm cm}$ = 14,22 GeV

[50] ARTUSO 94 reports the combined result from three independent methods, one of which (23% of the $\tau^- \rightarrow h^-\pi^0\nu_\tau$) is normalized to the inclusive one-prong branching fraction, taken as 0.854 ± 0.004. Renormalization to the present value causes negligible change.

[51] ALBRECHT 92Q with 0.5% added to remove their correction for $\tau^- \rightarrow K^*(892)^-\nu_\tau$ background.

[52] AKERS 94E quote $(26.25 \pm 0.36 \pm 0.52) \times 10^{-2}$; we subtract 0.27% from their number to correct for $\tau^- \rightarrow h^- K^0_L \nu_\tau$.

[53] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.


WEIGHTED AVERAGE
25.69±0.22 (Error scaled by 1.5)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{13}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
25.32±0.15 OUR FIT	Error includes scale factor of 1.1.					
25.31±0.18 OUR AVERAGE						
25.30±0.15±0.13	avg		[54] BUSKULIC	96	ALEP	LEP 1991–1993 data
25.36±0.44	avg		[55] ARTUSO	94	CLEO	$E^{ee}_{\rm cm}$ = 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
21.5 ±0.4 ±1.9		4400	[56,57] ALBRECHT	88L	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
23.0 ±1.3 ±1.7		582	ADLER	87B	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
25.8 ±1.7 ±2.5			[58] BURCHAT	87	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
22.3 ±0.6 ±1.4		629	[57] YELTON	86	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV

[54] Not independent of BUSKULIC 96 B($h^-\pi^0\nu_\tau$) and B($K^-\pi^0\nu_\tau$) values.

[55] Not independent of ARTUSO 94 B($h^-\pi^0\nu_\tau$) and BATTLE 94 B($K^-\pi^0\nu_\tau$) values.

[56] The authors divide by $(\Gamma_3 + \Gamma_5 + \Gamma_9 + \Gamma_{10})/\Gamma = 0.467$ to obtain this result.

[57] Experiment had no hadron identification. Kaon corrections were made, but insufficient information is given to permit their removal.

[58] BURCHAT 87 value is not independent of YELTON 86 value. Nonresonant decays included.

$\Gamma(\pi^-\pi^0\,{\rm non}\text{-}\rho(770)\,\nu_\tau)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE (%)	DOCUMENT ID		TECN	COMMENT
0.3 ±0.1 ±0.3	[59] BEHREND	84	CELL	$E^{ee}_{\rm cm}$ = 14,22 GeV

[59] BEHREND 84 assume a flat nonresonant mass distribution down to the $\rho(770)$ mass, using events with mass above 1300 to set the level.

$\Gamma(K^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{15}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.52±0.05 OUR FIT					
0.52±0.06 OUR AVERAGE					
0.52±0.04±0.05	395	BUSKULIC	96	ALEP	LEP 1991–1993 data
0.51±0.10±0.07	37	BATTLE	94	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.53±0.05±0.07	220	BUSKULIC	94E	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- \geq 2\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{16}/Γ

$\Gamma_{16}/\Gamma = (\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{32}+0.157\Gamma_{34}+0.157\Gamma_{36}+0.157\Gamma_{38}+0.0246\Gamma_{41}+0.319\Gamma_{110})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

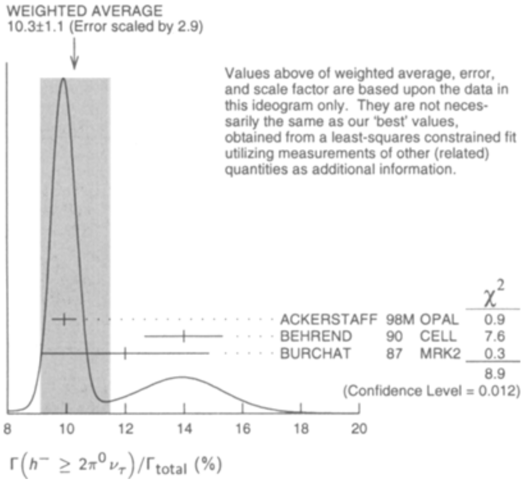
VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
10.79±0.16 OUR FIT	Error includes scale factor of 1.2.					
10.3 ±1.1 OUR AVERAGE	Error includes scale factor of 2.9. See the ideogram below.					
9.91±0.31±0.27	f&a		ACKERSTAFF	98M	OPAL	1991–1995 LEP runs
14.0 ±1.2 ±0.6	avg	938	[60] BEHREND	90	CELL	$E^{ee}_{\rm cm}$ = 35 GeV
12.0 ±1.4 ±2.5	f&a		[61] BURCHAT	87	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
9.89±0.34±0.55			[62] AKERS	94E	OPAL	Repl. by ACKERSTAFF 98M
13.9 ±2.0 $^{+1.9}_{-2.2}$			[63] AIHARA	86E	TPC	$E^{ee}_{\rm cm}$ = 29 GeV

[60] No independent of BEHREND 90 $\Gamma(h^- 2\pi^0\nu_\tau$ (exp. K^0)) and $\Gamma(h^- \geq 3\pi^0\nu_\tau)$.

[61] Error correlated with BURCHAT 87 $\Gamma(\rho^-\nu_e)/\Gamma$(total) value.

[62] AKERS 94E not independent of AKERS 94E B($h^- \geq 1\pi^0\nu_\tau$) and B($h^-\pi^0\nu_\tau$) measurements.

[63] AIHARA 86E (TPC) quote B($2\pi^0\pi^-\nu_\tau$) + 1.6B($3\pi^0\pi^-\nu_\tau$) + 1.1B($\pi^0\eta\pi^-\nu_\tau$).



$\Gamma(h^- 2\pi^0 \nu_\tau)/\Gamma_{\rm total}$ Γ_{17}/Γ

$\Gamma_{17}/\Gamma = (\Gamma_{19}+\Gamma_{20}+0.157\Gamma_{32}+0.157\Gamma_{34})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
9.39±0.14 OUR FIT	Error includes scale factor of 1.2.			
9.48±0.13±0.10	12k	[64] BUSKULIC 96	ALEP	LEP 1991–1993 data

[64] BUSKULIC 96 quote 9.29 ± 0.13 ± 0.10. We add 0.19 to undo their correction for $\tau^- \to h^- K^0 \nu_\tau$.

$\Gamma(h^- 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{18}/Γ

$\Gamma_{18}/\Gamma = (\Gamma_{19}+\Gamma_{20})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. f&a marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
9.23±0.14 OUR FIT	Error includes scale factor of 1.2.				
8.95±0.33 OUR AVERAGE	Error includes scale factor of 1.1.				
8.88±0.37±0.42	f&a	1060	ACCIARRI 95	L3	1992 LEP run
8.96±0.16±0.44	avg		[65] PROCARIO 93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
10.38±0.66±0.82	f&a	809	[66] DECAMP 92C	ALEP	1989–1990 LEP runs
$5.7 \pm 0.5 {}^{+1.7}_{-1.0}$	f&a	133	[67] ANTREASYAN 91	CBAL	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
10.0 ±1.5 ±1.1	f&a	333	[68] BEHREND 90	CELL	$E^{ee}_{\rm cm}$= 35 GeV
8.7 ±0.4 ±1.1	f&a	815	[69] BAND 87	MAC	$E^{ee}_{\rm cm}$= 29 GeV
6.0 ±3.0 ±1.8	f&a		BEHREND 84	CELL	$E^{ee}_{\rm cm}$= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.2 ±0.6 ±1.2			[70] GAN 87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV

[65] PROCARIO 93 entry is obtained from $B(h^- 2\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ using ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$.

[66] We subtract 0.0015 to account for $\tau^- \to K^*(892)^- \nu_\tau$ contribution.

[67] ANTREASYAN 91 subtract 0.001 to account for the $\tau^- \to K^*(892)^- \nu_\tau$ contribution.

[68] BEHREND 90 subtract 0.002 to account for the $\tau^- \to K^*(892)^- \nu_\tau$ contribution.

[69] BAND 87 assume $B(\pi^- 3\pi^0 \nu_\tau) = 0.01$ and $B(\pi^- \pi^0 \eta \nu_\tau) = 0.005$.

[70] GAN 87 analysis use photon multiplicity distribution.

$\Gamma(h^- 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma(h^- \pi^0 \nu_\tau)$ Γ_{18}/Γ_{12}

$\Gamma_{18}/\Gamma_{12} = (\Gamma_{19}+\Gamma_{20})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.357±0.006 OUR FIT	Error includes scale factor of 1.2.		
0.342±0.006±0.016	[71] PROCARIO 93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

[71] PROCARIO 93 quote 0.345 ± 0.006 ± 0.016 after correction for 2 kaon backgrounds assuming $B(K^{*-} \nu_\tau)$=1.42 ± 0.18% and $B(h^- K^0 \pi^0 \nu_\tau)$=0.48 ± 0.48%. We multiply by 0.990 ± 0.010 to remove these corrections to $B(h^- \pi^0 \nu_\tau)$.

$\Gamma(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{19}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID	TECN	COMMENT
9.15±0.15 OUR FIT	Error includes scale factor of 1.2.			
9.21±0.13±0.11	**avg**	[72] BUSKULIC 96	ALEP	LEP 1991–1993 data

[72] Not independent of BUSKULIC 96 $B(h^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ and $B(K^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ values.

$\Gamma(K^- 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{20}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.080±0.027 OUR FIT				
0.081±0.027 OUR AVERAGE				
0.08 ±0.02 ±0.02	59	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.09 ±0.10 ±0.03	3	[73] BATTLE 94	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04 ±0.03 ±0.02	11	BUSKULIC 94E	ALEP	Repl. by BUSKULIC 96

[73] BATTLE 94 quote 0.14 ± 0.10 ± 0.03 or < 0.3% at 90% CL. We subtract (0.05 ± 0.02)% to account for $\tau^- \to K^-(K^0 \to \pi^0\pi^0)\nu_\tau$ background.

$\Gamma(h^- \geq 3\pi^0 \nu_\tau)/\Gamma_{\rm total}$ Γ_{21}/Γ

$\Gamma_{21}/\Gamma = (\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{36}+0.157\Gamma_{38}+0.0246\Gamma_{41}+0.319\Gamma_{110})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.40±0.11 OUR FIT	Error includes scale factor of 1.1.				
1.8 ±0.6 OUR AVERAGE	Error includes scale factor of 1.1.				
1.53±0.40±0.46	f&a	186	DECAMP 92C	ALEP	1989–1990 LEP runs
3.2 ±1.0 ±1.0	f&a		BEHREND 90	CELL	$E^{ee}_{\rm cm}$= 35 GeV

$\Gamma(h^- 3\pi^0 \nu_\tau)/\Gamma_{\rm total}$ Γ_{22}/Γ

$\Gamma_{22}/\Gamma = (\Gamma_{23}+\Gamma_{24}+0.157\Gamma_{36}+0.157\Gamma_{38})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.23±0.10 OUR FIT	Error includes scale factor of 1.1.				
1.22±0.10 OUR AVERAGE					
1.24±0.09±0.11	f&a	2.3k	[74] BUSKULIC 96	ALEP	LEP 1991–1993 data
1.70±0.24±0.38	f&a	293	ACCIARRI 95	L3	1992 LEP run
1.15±0.08±0.13	avg		[75] PROCARIO 93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0 {}^{+1.4}_{-0.1} {}^{+1.1}_{-0.1}$			[76] GAN 87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV

[74] BUSKULIC 96 quote $B(h^- 3\pi^0 \nu_\tau (\text{ex. } K^0))$ = 1.17 ± 0.09 ± 0.11. We add 0.07 to remove their correction for K^0 backgrounds.

[75] PROCARIO 93 entry is obtained from $B(h^- 3\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ using ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$.

[76] Highly correlated with GAN 87 $\Gamma(\eta\pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$ value. Authors quote $B(\pi^\pm 3\pi^0 \nu_\tau) + 0.67B(\pi^\pm \eta \pi^0 \nu_\tau)$ = 0.047 ± 0.010 ± 0.011.

$\Gamma(h^- 3\pi^0 \nu_\tau)/\Gamma(h^- \pi^0 \nu_\tau)$ Γ_{22}/Γ_{12}

$\Gamma_{22}/\Gamma_{12} = (\Gamma_{23}+\Gamma_{24}+0.157\Gamma_{36}+0.157\Gamma_{38})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.048±0.004 OUR FIT	Error includes scale factor of 1.1.		
0.044±0.003±0.005	[77] PROCARIO 93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

[77] PROCARIO 93 quote 0.041 ± 0.003 ± 0.005 after correction for 2 kaon backgrounds assuming $B(K^{*-} \nu_\tau)$=1.42 ± 0.18% and $B(h^- K^0 \pi^0 \nu_\tau)$=0.48 ± 0.48%. We add 0.003 ± 0.003 and multiply the sum by 0.990 ± 0.010 to remove these corrections.

$\Gamma(\pi^- 3\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{23}/Γ

VALUE (%)	DOCUMENT ID
1.11±0.14 OUR FIT	

$\Gamma(K^- 3\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{24}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
$0.043^{+0.100}_{-0.029}$ OUR FIT			
0.05 ±0.13	[78] BUSKULIC 94E	ALEP	1991-1992 LEP runs

[78] BUSKULIC 94E quote $B(K^- \geq 0\pi^0 \geq 0K^0 \nu_\tau) - [B(K^- \nu_\tau) + B(K^- \pi^0 \nu_\tau) + B(K^- K^0 \nu_\tau) + B(K^- \pi^0 \pi^0 \nu_\tau) + B(K^- \pi^0 K^0 \nu_\tau)]$ = 0.05 ± 0.13% accounting for common systematic errors in BUSKULIC 94E and BUSKULIC 94F measurements of these modes. We assume $B(K^- \geq 2K^0 \nu_\tau)$ and $B(K^- \geq 4\pi^0 \nu_\tau)$ are negligible.

$\Gamma(h^- 4\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{25}/Γ

$\Gamma_{25}/\Gamma = (\Gamma_{26}+0.319\Gamma_{110})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.17±0.06 OUR FIT				
0.16±0.06 OUR AVERAGE				
0.16±0.04±0.09	232	[79] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.16±0.05±0.05		[80] PROCARIO 93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

[79] BUSKULIC 96 quote result for $\tau^- \to h^- \geq 4\pi^0 \nu_\tau$. We assume $B(h^- \geq 5\pi^0 \nu_\tau)$ is negligible.

[80] PROCARIO 93 quotes $B(h^- 4\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ =0.006 ± 0.002 ± 0.002. We multiply by the ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$ to obtain $B(h^- 4\pi^0 \nu_\tau)$. PROCARIO 93 assume $B(h^- \geq 5\ \pi^0 \nu_\tau)$ is small and do not correct for it.

$\Gamma(h^- 4\pi^0 \nu_\tau (\text{ex.}K^0,\eta))/\Gamma_{\rm total}$ Γ_{26}/Γ

VALUE (%)	DOCUMENT ID
0.11±0.06 OUR FIT	

$\Gamma(K^- \geq 0\pi^0 \geq 0K^0\, \nu_\tau)/\Gamma_{\rm total}$ Γ_{27}/Γ

$\Gamma_{27}/\Gamma = (\Gamma_{10}+\Gamma_{15}+\Gamma_{20}+\Gamma_{24}+\Gamma_{34}+\Gamma_{38})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.66±0.10 OUR FIT					
1.69±0.07 OUR AVERAGE					
1.70±0.05±0.06	avg	1610	[81] BUSKULIC 96	ALEP	LEP 1991–1993 data
1.54±0.24	f&a		ABREU 94K	DLPH	LEP 1992 Z data
1.70±0.12±0.19	f&a	202	[82] BATTLE 94	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
1.6 ±0.4 ±0.2	f&a	35	AIHARA 87B	TPC	$E^{ee}_{\rm cm}$= 29 GeV
1.71±0.29	f&a	53	MILLS 84	DLCO	$E^{ee}_{\rm cm}$= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.60±0.07±0.12		967	[83] BUSKULIC 94E	ALEP	Repl. by BUSKULIC 96

[81] Not independent of BUSKULIC 96 B($K^-\nu_\tau$), B($K^-\pi^0\nu_\tau$), B($K^-2\pi^0\nu_\tau$), B($K^-K^0\nu_\tau$), and B($K^-K^0\pi^0\nu_\tau$) values.

[82] BATTLE 94 quote 1.60 ± 0.12 ± 0.19. We add 0.10 ± 0.02 to correct for their rejection of $K^0_S \rightarrow \pi^+\pi^-$ decays.

[83] Not independent of BUSKULIC 94E B($K^-\nu_\tau$), B($K^-\pi^0\nu_\tau$), B($K^-2\pi^0\nu_\tau$), B($K^-K^0\nu_\tau$), and B($K^-K^0\pi^0\nu_\tau$) values.

$\Gamma(K^- \geq 1\,(\pi^0 \text{ or } K^0)\,\nu_\tau)/\Gamma_{\rm total}$ Γ_{28}/Γ

$\Gamma_{28}/\Gamma = (\Gamma_{15}+\Gamma_{20}+\Gamma_{24}+\Gamma_{34}+\Gamma_{38})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.95±0.10 OUR FIT					
0.76±0.23 OUR AVERAGE					
0.69±0.25	avg		[84] ABREU 94K	DLPH	LEP 1992 Z data
1.2 ±0.5 $^{+0.2}_{-0.4}$	f&a	9	AIHARA 87B	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[84] Not independent of ABREU 94K B($K^-\nu_\tau$) and B($K^- \geq 0$ neutralsν_τ) measurements.

$\Gamma(K^0(\text{particles})^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{29}/Γ

$\Gamma_{29}/\Gamma = (\Gamma_{32}+\Gamma_{34}+\Gamma_{36}+\Gamma_{38}+\Gamma_{41})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.66±0.09 OUR FIT	Error includes scale factor of 1.4.			
1.94±0.13 OUR AVERAGE				
1.94±0.12±0.12	929	[85] BARATE 98E	ALEP	1991–1995 LEP runs
1.94±0.18±0.12	141	[86] AKERS 94G	OPAL	$E^{ee}_{\rm cm}$= 88–94 GeV

[85] BARATE 98E measure $\Gamma(K^0_S(\text{particles})^-\nu_\tau)/\Gamma_{\rm total}$ = (0.970 ± 0.058 ± 0.062)%. We multiply this by 2 to obtain the listed value.

[86] AKERS 94G measure $\Gamma(K^0_S(\text{particles})^-\nu_\tau)/\Gamma_{\rm total}$ = 0.97 ± 0.09 ± 0.06.

$\Gamma(h^-\overline{K}^0 \geq 0 \text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\rm total}$ Γ_{30}/Γ

$\Gamma_{30}/\Gamma = (\Gamma_{32}+\Gamma_{34}+\Gamma_{36}+\Gamma_{38}+0.657\Gamma_{41})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.62±0.09 OUR FIT	Error includes scale factor of 1.4.			
1.3 ±0.3	44	TSCHIRHART 88	HRS	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(h^-\overline{K}^0\nu_\tau)/\Gamma_{\rm total}$ $\Gamma_{31}/\Gamma = (\Gamma_{32}+\Gamma_{34})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.99 ±0.08 OUR FIT	Error includes scale factor of 1.5.				
0.90 ±0.07 OUR AVERAGE					
1.01 ±0.11 ±0.07	avg	555	[87] BARATE 98E	ALEP	1991–1995 LEP runs
0.855±0.036±0.073	f&a	1242	COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

[87] Not independent of BARATE 98E B($\tau^- \rightarrow \pi^-\overline{K}^0\nu_\tau$) and B($\tau^- \rightarrow K^-K^0\nu_\tau$) values.

$\Gamma(\pi^-\overline{K}^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{32}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.83 ±0.08 OUR FIT	Error includes scale factor of 1.4.				
0.78 ±0.06 OUR AVERAGE					
0.855±0.117±0.066	avg	509	[88] BARATE 98E	ALEP	1991–1995 LEP runs
0.79 ±0.10 ±0.09	f&a	98	[89] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.704±0.041±0.072	avg		[90] COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
0.95 ±0.15 ±0.06	f&a		[91] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.88 ±0.14 ±0.09		53	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[88] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+\pi^-$ decays. Not independent of BARATE 98E B(K^0particles$^-\nu_\tau$) value.

[89] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

[90] Not independent of COAN 96 B($h^-K^0\nu_\tau$) and B($K^-K^0\nu_\tau$) measurements.

[91] ACCIARRI 95F do not identify π^-/K^- and assume B($K^-K^0\nu_\tau$) = (0.29 ± 0.12)%.

$\Gamma(\pi^-\overline{K}^0(\text{non-}K^*(892)^-)\nu_\tau)/\Gamma_{\rm total}$ Γ_{33}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	95	ACCIARRI 95F	L3	1991–1993 LEP runs

$\Gamma(K^-K^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{34}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.159±0.024 OUR FIT				
0.161±0.024 OUR AVERAGE				
0.158±0.042±0.017	46	[92] BARATE 98E	ALEP	1991–1995 LEP runs
0.26 ±0.09 ±0.02	13	[93] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.151±0.021±0.022	111	COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29 ±0.12 ±0.03	8	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[92] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+\pi^-$ decays.

[93] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(h^-\overline{K}^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ $\Gamma_{35}/\Gamma = (\Gamma_{36}+\Gamma_{38})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.55 ±0.05 OUR FIT					
0.50 ±0.06 OUR AVERAGE	Error includes scale factor of 1.2.				
0.446±0.052±0.046	avg	157	[94] BARATE 98E	ALEP	1991–1995 LEP runs
0.562±0.050±0.048	f&a	264	COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

[94] Not independent of BARATE 98E B($\tau^- \rightarrow \pi^-\overline{K}^0\pi^0\tau$) and B($\tau^- \rightarrow K^-K^0\pi^0\nu_\tau$) values.

$\Gamma(\pi^-\overline{K}^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{36}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.39 ±0.05 OUR FIT					
0.36 ±0.05 OUR AVERAGE					
0.294±0.073±0.037	f&a	142	[95] BARATE 98E	ALEP	1991–1995 LEP runs
0.32 ±0.11 ±0.05	f&a	23	[96] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.417±0.058±0.044	avg		[97] COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
0.41 ±0.12 ±0.03	f&a		[98] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.33 ±0.14 ±0.07		9	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[95] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+\pi^-$ decays.

[96] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

[97] Not independent of COAN 96 B($h^-K^0\pi^0\nu_\tau$) and B($K^-K^0\pi^0\nu_\tau$) measurements.

[98] ACCIARRI 95F do not identify π^-/K^- and assume B($K^-K^0\pi^0\nu_\tau$) = (0.05 ± 0.05)%.

$\Gamma(\overline{K}^0\rho^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{37}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.188±0.054±0.038	[99] BARATE 98E	ALEP	1991–1995 LEP runs

[99] BARATE 98E determine the $\overline{K}^0\rho^-$ fraction in $\tau^- \rightarrow \pi^-\overline{K}^0\pi^0\nu_\tau$ decays to be (0.64 ± 0.09 ± 0.10) and multiply their B($\pi^-\overline{K}^0\pi^0\nu_\tau$) measurement by this fraction to obtain the quoted result.

$\Gamma(K^-K^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{38}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.151±0.029 OUR FIT				
0.133±0.031 OUR AVERAGE				
0.152±0.076±0.021	15	[100] BARATE 98E	ALEP	1991–1995 LEP runs
0.10 ±0.05 ±0.03	5	[101] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.145±0.036±0.020	32	COAN 96	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05 ±0.05 ±0.01	1	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[100] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+\pi^-$ decays.

[101] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(\pi^-\overline{K}^0\pi^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{39}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.58±0.33±0.14	5	[102] BARATE 98E	ALEP	1991–1995 LEP runs

[102] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+\pi^-$ decays.

$\Gamma(K^-K^0\pi^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.39 × 10^{-3}	95	BARATE 98E	ALEP	1991–1995 LEP runs

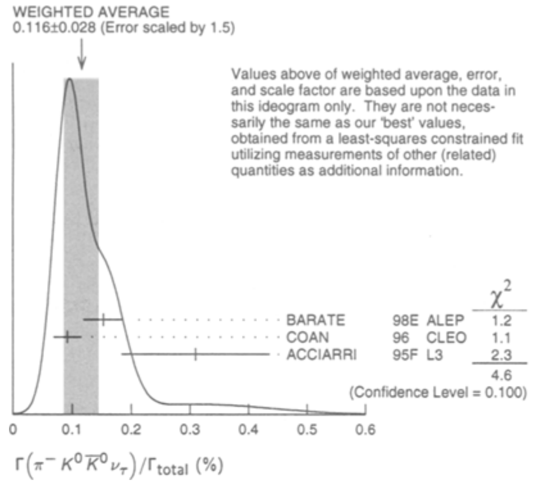
$\Gamma(\pi^- K^0 \overline{K}^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{41}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.121±0.021 OUR FIT	Error includes scale factor of 1.2.				
0.116±0.028 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
0.153±0.030±0.016	f&a	74	[103] BARATE 98E	ALEP	1991–1995 LEP runs
0.092±0.020±0.012	avg	42	[104] COAN 96	CLEO	$E^{ee}_{\text{cm}} \approx$ 10.6 GeV
0.31 ±0.12 ±0.04	f&a		ACCIARRI 95F	L3	1991–1993 LEP runs

[103] BARATE 98E obtain this value by adding twice their $B(\pi^- K^0_S K^0_S \nu_\tau)$ value to their $B(\pi^- K^0_S K^0_L \nu_\tau)$ value.

[104] We multiply the COAN 96 measurement $B(h^- K^0_S K^0_S \nu_\tau) = (0.023 \pm 0.005 \pm 0.003)\%$ by 4 to obtain the listed value. This factor of 1/4 is uncertain, and might be as large as 1/2, due to Bose-Einstein correlations and the resonant parentage of this state.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^- K^0_S K^0_S \nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{42}/\Gamma = \frac{1}{4}\Gamma_{41}/\Gamma$

Bose-Einstein correlations might make the mixing fraction different than 1/4.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.030±0.005 OUR FIT	Error includes scale factor of 1.2.			
0.024±0.005 OUR AVERAGE				
0.026±0.010±0.005	6	BARATE 98E	ALEP	1991–1995 LEP runs
0.023±0.005±0.003	42	COAN 96	CLEO	$E^{ee}_{\text{cm}} \approx$ 10.6 GeV

$\Gamma(\pi^- K^0_S K^0_L \nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{43}/\Gamma = \frac{1}{2}\Gamma_{41}/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.060±0.010 OUR FIT	Error includes scale factor of 1.2.				
0.101±0.023±0.013	**avg**	68	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^0_S K^0_S \pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{44}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.020	95	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^0_S K^0_L \pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{45}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.031±0.011±0.005	11	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(K^- K^0 \geq 0\,\text{neutrals}\ \nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{46}/\Gamma = (\Gamma_{34}+\Gamma_{38})/\Gamma$

VALUE (%)	DOCUMENT ID
0.31±0.04 OUR FIT	

$\Gamma(K^0 h^+ h^- h^- \geq 0\,\text{neutrals}\ \nu_\tau)/\Gamma_{\text{total}}$ Γ_{47}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	95	TSCHIRHART 88	HRS	E^{ee}_{cm} = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.27	90	BELTRAMI 85	HRS	E^{ee}_{cm} = 29 GeV

$\Gamma(K^0 h^+ h^- h^- \nu_\tau)/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.023±0.019±0.007	6	[105] BARATE 98E	ALEP	1991–1995 LEP runs

[105] BARATE 98E reconstruct K^0's using $K^0_S \rightarrow \pi^+ \pi^-$ decays.

$\Gamma(h^- h^- h^+ \geq 0\text{neut.}\ \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$ Γ_{49}/Γ

$\Gamma_{49}/\Gamma = (0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.4508\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
15.18± 0.13 OUR FIT	Error includes scale factor of 1.2.				
14.8 ± 0.4 OUR AVERAGE					
14.4 ± 0.6 ±0.3	f&a		ADEVA 91F	L3	E^{ee}_{cm} = 88.3–94.3 GeV
15.0 ± 0.4 ±0.3	f&a		BEHREND 89B	CELL	E^{ee}_{cm} = 14–47 GeV
15.1 ± 0.8 ±0.6	f&a		AIHARA 87B	TPC	E^{ee}_{cm} = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
13.5 ± 0.3 ±0.3			ABACHI 89B	HRS	E^{ee}_{cm} = 29 GeV
12.8 ± 1.0 ±0.7			[106] BURCHAT 87	MRK2	E^{ee}_{cm} = 29 GeV
12.1 ± 0.5 ±1.2			RUCKSTUHL 86	DLCO	E^{ee}_{cm} = 29 GeV
12.8 ± 0.5 ±0.8		1420	SCHMIDKE 86	MRK2	E^{ee}_{cm} = 29 GeV
15.3 ± 1.1 $^{+1.3}_{-1.6}$		367	ALTHOFF 85	TASS	E^{ee}_{cm} = 34.5 GeV
13.6 ± 0.5 ±0.8			BARTEL 85F	JADE	E^{ee}_{cm} = 34.6 GeV
12.2 ± 1.3 ±3.9			[107] BERGER 85	PLUT	E^{ee}_{cm} = 34.6 GeV
13.3 ± 0.3 ±0.6			FERNANDEZ 85	MAC	E^{ee}_{cm} = 29 GeV
24 ± 6		35	BRANDELIK 80	TASS	E^{ee}_{cm} = 30 GeV
32 ± 5		692	[108] BACINO 78B	DLCO	E^{ee}_{cm} = 3.1–7.4 GeV
35 ±11			[108] BRANDELIK 78	DASP	Assumes $V-A$ decay
18 ± 6.5		33	[108] JAROS 78	MRK1	$E^{ee}_{\text{cm}} > 6$ GeV

[106] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[107] Not independent of BERGER 85 $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(h^- \geq 1\,\text{neutrals}\,\nu_\tau)/\Gamma_{\text{total}}$, and $\Gamma(h^- \geq 0 K^0_L\ \nu_\tau)/\Gamma_{\text{total}}$, and therefore not used in the fit.

[108] Low energy experiments are not in average or fit because the systematic errors in background subtraction are judged to be large.

$\Gamma(h^- h^- h^+ \geq 0\,\text{neutrals}\ \nu_\tau(\text{ex.}\ K^0_S \rightarrow \pi^+ \pi^-))/\Gamma_{\text{total}}$ Γ_{50}/Γ

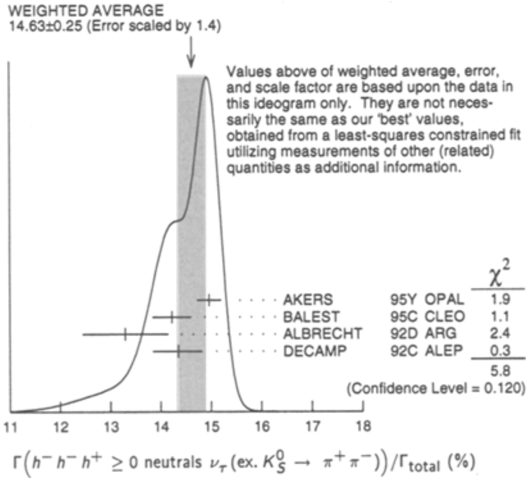
$\Gamma_{50}/\Gamma = (\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
14.60±0.13 OUR FIT	Error includes scale factor of 1.2.				
14.63±0.25 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
14.96±0.09±0.22	f&a	10.4k	AKERS 95Y	OPAL	1991–1994 LEP runs
14.22±0.10±0.37	avg		[109] BALEST 95C	CLEO	$E^{ee}_{\text{cm}} \approx$ 10.6 GeV
13.3 ±0.3 ±0.8	f&a		[110] ALBRECHT 92D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV
14.35 $^{+0.40}_{-0.45}$ ±0.24	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
15.26±0.26±0.22			ACTON 92H	OPAL	Repl. by AKERS 95Y

[109] Not independent of BALEST 95C $B(h^- h^- h^+ \nu_\tau)$ and $B(h^- h^- h^+ \pi^0 \nu_\tau)$ values, and BORTOLETTO 93 $B(h^- h^- h^+ 2\pi^0 \nu_\tau)/B(h^- h^- h^+ \geq 0\,\text{neutrals}\ \nu_\tau)$ value.

[110] This ALBRECHT 92D value is not independent of their $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma^2_{\text{total}}$ value.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^-\pi^+\pi^- \geq 0$ neutrals $\nu_\tau)/\Gamma(h^-h^-h^+ \geq 0$neut. ν_τ("3-prong")) Γ_{51}/Γ_{49}

$\Gamma_{51}/\Gamma_{49} = (0.3431\Gamma_{32}+0.3431\Gamma_{36}+0.1078\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})/(0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.4508\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.962±0.005 OUR FIT	Error includes scale factor of 1.1.				
0.945±0.019	490	[111] BAUER	94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[111] BAUER 94 quote B($\pi^-\pi^+\pi^- \geq$ 0 neutrals ν_τ) = 0.1329 ± 0.0027. We divide by 0.1406, their assumed value for B("3prong").

$\Gamma(h^-h^-h^+\nu_\tau)/\Gamma_{\rm total}$ Γ_{52}/Γ

$\Gamma_{52}/\Gamma = (0.3431\Gamma_{32}+0.3431\Gamma_{34}+\Gamma_{57}+\Gamma_{79}+\Gamma_{84}+0.0221\Gamma_{125})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.96±0.10 OUR FIT	Error includes scale factor of 1.1.					
9.7 ±0.4 OUR AVERAGE	Error includes scale factor of 3.1. See the ideogram below.					
7.6 ±0.1 ±0.5	avg	7.5k	[112] ALBRECHT	96E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
9.92±0.10±0.09	f&a	11.2k	[113] BUSKULIC	96	ALEP	LEP 1991–1993 data
9.49±0.36±0.63	f&a		DECAMP	92C	ALEP	1989–1990 LEP runs
8.7 ±0.7 ±0.3	f&a	694	[114] BEHREND	90	CELL	$E^{ee}_{\rm cm}$= 35 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
7.0 ±0.3 ±0.7		1566	[115] BAND	87	MAC	$E^{ee}_{\rm cm}$= 29 GeV
6.7 ±0.8 ±0.9			[116] BURCHAT	87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
6.4 ±0.4 ±0.9			[117] RUCKSTUHL	86	DLCO	$E^{ee}_{\rm cm}$= 29 GeV
7.8 ±0.5 ±0.8		890	SCHMIDKE	86	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
8.4 ±0.4 ±0.7		1255	[117] FERNANDEZ	85	MAC	$E^{ee}_{\rm cm}$= 29 GeV
9.7 ±2.0 ±1.3			BEHREND	84	CELL	$E^{ee}_{\rm cm}$= 14,22 GeV

[112] ALBRECHT 96E not independent of ALBRECHT 93C $\Gamma(h^-h^-h^+\nu_\tau$(ex. K^0) × Γ(particle$^-$ ≥ 0 neutrals ≥ 0$K^0_L\nu_\tau)/\Gamma^2_{\rm total}$ value.

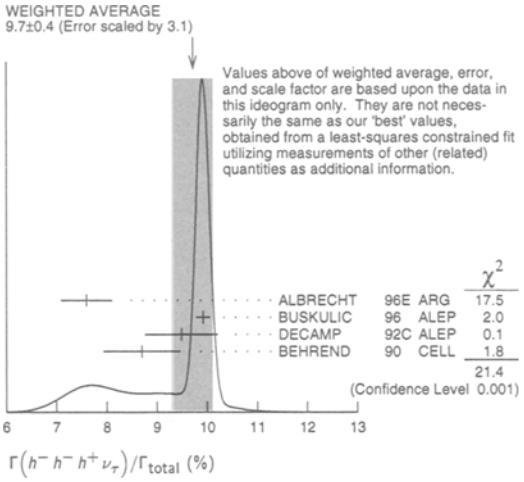
[113] BUSKULIC 96 quote B($h^-h^-h^+\nu_\tau$(ex. K^0)) = 9.50 ± 0.10 ± 0.11. We add 0.42 to remove their K^0 correction and reduce the systematic error accordingly.

[114] BEHREND 90 subtract 0.3% to account for the $\tau^- \rightarrow K^*(892)^-\nu_\tau$ contribution to measured events.

[115] BAND 87 subtract for charged kaon modes; not independent of FERNANDEZ 85 value.

[116] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[117] Value obtained by multiplying paper's R = B($h^-h^-h^+\nu_\tau$)/B(3-prong) by B(3-prong) = 0.143 and subtracting 0.3% for $K^*(892)$ background.



$\Gamma(h^-h^-h^+\nu_\tau)/\Gamma(h^-h^-h^+ \geq 0$neut. ν_τ("3-prong")) Γ_{52}/Γ_{49}

$\Gamma_{52}/\Gamma_{49} = (0.3431\Gamma_{32}+0.3431\Gamma_{34}+\Gamma_{57}+\Gamma_{79}+\Gamma_{84}+0.0221\Gamma_{125})/(0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.4508\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})$

This branching fractions is not independent of values for $\Gamma(h^-h^-h^+\nu_\tau)/\Gamma_{\rm total}$ and $\Gamma(h^-h^-h^+ \geq$ 0neut. ν_τ("3-prong"))$/\Gamma_{\rm total}$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.656±0.006 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.03 ±0.06	RUCKSTUHL	86	DLCO	$E^{ee}_{\rm cm}$= 29 GeV
0.61 ±0.03 ±0.05	FERNANDEZ	85	MAC	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(h^-h^-h^+\nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ Γ_{53}/Γ

$\Gamma_{53}/\Gamma = (\Gamma_{57}+\Gamma_{79}+\Gamma_{84}+0.0221\Gamma_{125})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.62±0.10 OUR FIT	Error includes scale factor of 1.1.					
9.57±0.11 OUR AVERAGE						
9.50±0.10±0.11	avg	11.2k	[118] BUSKULIC	96	ALEP	LEP 1991–1993 data
9.87±0.10±0.24	avg		[119] AKERS	95Y	OPAL	1991–1994 LEP runs
9.51±0.07±0.20	f&a	37.7k	BALEST	95C	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV

[118] Not independent of BUSKULIC 96 B($h^-h^-h^+\nu_\tau$) value.

[119] Not independent of AKERS 95Y B($h^-h^-h^+ \geq$ 0 neutralsν_τ(ex. $K^0_S \rightarrow \pi^+\pi^-$)) and B($h^-h^-h^+\nu_\tau$(ex. K^0))/B($h^-h^-h^+ \geq$ 0 neutralsν_τ(ex. $K^0_S \rightarrow \pi^+\pi^-$)) values.

$\Gamma(h^-h^-h^+\nu_\tau(\text{ex.}K^0))/\Gamma(h^-h^-h^+ \geq 0$ neutrals $\nu_\tau(\text{ex.}\ K^0_S \rightarrow \pi^+\pi^-))$ Γ_{53}/Γ_{50}

$\Gamma_{53}/\Gamma_{50} = (\Gamma_{57}+\Gamma_{79}+\Gamma_{84}+0.0221\Gamma_{125})/(\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.659±0.006 OUR FIT	Error includes scale factor of 1.1.			
0.660±0.004±0.014	AKERS	95Y	OPAL	1991–1994 LEP runs

$\Gamma(h^-h^-h^+\nu_\tau(\text{ex.}K^0,\omega))/\Gamma_{\rm total}$ $\Gamma_{54}/\Gamma = (\Gamma_{57}+\Gamma_{79}+\Gamma_{84})/\Gamma$

VALUE (%)	DOCUMENT ID
9.57±0.10 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau)/\Gamma_{\rm total}$ $\Gamma_{55}/\Gamma = (0.3431\Gamma_{32}+\Gamma_{57}+0.0221\Gamma_{125})/\Gamma$

VALUE (%)	DOCUMENT ID
9.56±0.11 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ $\Gamma_{56}/\Gamma = (0.3431\Gamma_{32}+\Gamma_{57})/\Gamma$

VALUE (%)	DOCUMENT ID
9.52±0.11 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0,\omega))/\Gamma_{\rm total}$ Γ_{57}/Γ

VALUE (%)	DOCUMENT ID
9.23±0.11 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(h^-h^-h^+ \geq 1$ neutrals $\nu_\tau)/\Gamma_{\rm total}$ Γ_{58}/Γ

$\Gamma_{58}/\Gamma = (0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.1077\Gamma_{41}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{81}+\Gamma_{85}+0.285\Gamma_{110}+0.888\Gamma_{125}+0.9101\Gamma_{126})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
5.18±0.11 OUR FIT	Error includes scale factor of 1.2.					
5.2 ±0.6 OUR AVERAGE						
5.6 ±0.7 ±0.3	avg	352	[120] BEHREND	90	CELL	$E^{ee}_{\rm cm}$= 35 GeV
4.2 ±0.5 ±0.9	f&a	203	[121] ALBRECHT	87L	ARG	$E^{ee}_{\rm cm}$= 10 GeV
6.2 ±2.3 ±1.7	f&a		BEHREND	84	CELL	$E^{ee}_{\rm cm}$= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
6.1 ±0.8 ±0.9			[122] BURCHAT	87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
7.6 ±0.4 ±0.9			[123,124] RUCKSTUHL	86	DLCO	$E^{ee}_{\rm cm}$= 29 GeV
4.7 ±0.5 ±0.8		530	[125] SCHMIDKE	86	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
5.6 ±0.4 ±0.7			[124] FERNANDEZ	85	MAC	$E^{ee}_{\rm cm}$= 29 GeV

[120] BEHREND 90 value is not independent of BEHREND 90 B($3h\nu_\tau \geq$ 1 neutrals) + B(5-prong).

[121] ALBRECHT 87L measure the product of branching ratios B($3\pi^\pm\pi^0\nu_\tau$) B(($e\overline{\nu}$or$\mu\overline{\nu}$orπor$K$orρ)ν_τ) = 0.029 and use the PDG 86 values for the second branching ratio which sum to 0.69 ± 0.03 to get the quoted value.

[122] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[123] Contributions from kaons and from >1π^0 are subtracted. Not independent of (3-prong + 0π^0) and (3-prong + ≥ 0π^0) values.

[124] Value obtained using paper's R = B($h^-h^-h^+\nu_\tau$)/B(3-prong) and current B(3-prong) = 0.143.

[125] Not independent of SCHMIDKE 86 $h^-h^-h^+\nu_\tau$ and $h^-h^-h^+(\geq 0\pi^0)\nu_\tau$ values.

$\Gamma(h^-h^-h^+ \geq 1$ neutrals $\nu_\tau(\text{ex.}\ K^0_S \rightarrow \pi^+\pi^-))/\Gamma_{\rm total}$ Γ_{59}/Γ

$\Gamma_{59}/\Gamma = (\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{81}+\Gamma_{85}+0.285\Gamma_{110}+0.888\Gamma_{125}+0.9101\Gamma_{126})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
4.98±0.11 OUR FIT	Error includes scale factor of 1.2.					
5.07±0.24 OUR AVERAGE						
5.09±0.10±0.23	avg		[126] AKERS	95Y	OPAL	1991–1994 LEP runs
4.95±0.29±0.65	f&a	570	DECAMP	92C	ALEP	1989–1990 LEP runs

[126] Not independent of AKERS 95Y B($h^-h^-h^+ \geq$ 0 neutralsν_τ(ex. $K^0_S \rightarrow \pi^+\pi^-$)) and B($h^-h^-h^+ \geq$ 0 neutralsν_τ(ex. K^0))/B($h^-h^-h^+ \geq$ 0 neutralsν_τ(ex. $K^0_S \rightarrow \pi^+\pi^-$)) values.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{60}/Γ

$\Gamma_{60}/\Gamma = (0.3431\Gamma_{36}+0.3431\Gamma_{38}+\Gamma_{65}+\Gamma_{81}+\Gamma_{85}+0.888\Gamma_{125}+0.0221\Gamma_{126})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
4.50±0.09 OUR FIT Error includes scale factor of 1.1.				
4.45±0.09±0.07	6.1k	[127] BUSKULIC 96	ALEP	LEP 1991–1993 data

[127] BUSKULIC 96 quote $B(h^- h^- h^+ \pi^0 \nu_\tau(\text{ex. } K^0)) = 4.30 \pm 0.09 \pm 0.09$. We add 0.15 to remove their K^0 correction and reduce the systematic error accordingly.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{61}/Γ

$\Gamma_{61}/\Gamma = (\Gamma_{65}+\Gamma_{81}+\Gamma_{85}+0.888\Gamma_{125}+0.0221\Gamma_{126})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
4.31±0.09 OUR FIT Error includes scale factor of 1.1.				
4.23±0.06±0.22	7.2k	BALEST 95C	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau(\text{ex. } K^0,\omega))/\Gamma_{\rm total}$ — $\Gamma_{62}/\Gamma = (\Gamma_{65}+\Gamma_{81}+\Gamma_{85})/\Gamma$

VALUE (%)	DOCUMENT ID
2.59±0.09 OUR FIT	

$\Gamma(\pi^- \pi^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$

$\Gamma_{63}/\Gamma = (0.3431\Gamma_{36}+\Gamma_{65}+0.888\Gamma_{125}+0.0221\Gamma_{126})/\Gamma$

VALUE (%)	DOCUMENT ID
4.35±0.10 OUR FIT	

$\Gamma(\pi^- \pi^+ \pi^- \pi^0 \nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ — $\Gamma_{64}/\Gamma = (\Gamma_{65}+0.888\Gamma_{125}+0.0221\Gamma_{126})/\Gamma$

VALUE (%)	DOCUMENT ID
4.22±0.10 OUR FIT	

$\Gamma(\pi^- \pi^+ \pi^- \pi^0 \nu_\tau(\text{ex.}K^0,\omega))/\Gamma_{\rm total}$ — Γ_{65}/Γ

VALUE (%)	DOCUMENT ID
2.49±0.10 OUR FIT	

$\Gamma(h^- (\rho\pi)^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{66}/Γ_{60}

$\Gamma_{66}/\Gamma_{60} = (\Gamma_{68}+\Gamma_{69}+\Gamma_{70})/\Gamma_{60}$

VALUE	DOCUMENT ID	TECN	COMMENT
0.64±0.07±0.03	[128] ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

[128] ALBRECHT 91D not independent of their $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, and $\Gamma(h^- \rho \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma((a_1(1260) h)^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{67}/Γ_{60}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.44	95	[129] ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

[129] ALBRECHT 91D not independent of their $\Gamma(h^- \omega \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau(\text{ex.}K^0))$, $\Gamma(h^- \rho \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, and $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma(h^- \rho \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{68}/Γ_{60}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.30±0.04±0.02	393	ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

$\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{69}/Γ_{60}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.10±0.03±0.04	142	ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

$\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{70}/Γ_{60}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.26±0.05±0.01	370	ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

$[\Gamma(h^- \rho^+ h^- \nu_\tau) + \Gamma(h^- \rho^- h^+ \nu_\tau)]/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — $(\Gamma_{69}+\Gamma_{70})/\Gamma_{60}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.33±0.06±0.01	475	[130] ALBRECHT 91D	ARG	$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV

[130] ALBRECHT 91D not independent of their $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ and $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{71}/Γ

$\Gamma_{71}/\Gamma = (0.1077\Gamma_{41}+\Gamma_{73}+0.236\Gamma_{110}+0.888\Gamma_{126})/\Gamma$

VALUE (%)	DOCUMENT ID
0.54±0.04 OUR FIT	

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{72}/Γ

$\Gamma_{72}/\Gamma = (\Gamma_{73}+0.236\Gamma_{110}+0.888\Gamma_{126})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.53±0.04 OUR FIT				
0.50±0.07±0.07	1.8k	BUSKULIC 96	ALEP	LEP 1991–1993 data

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau(\text{ex.}K^0))/\Gamma(h^- h^- h^+ \geq \text{0neut. } \nu_\tau(\text{"3-prong"}))$ — Γ_{72}/Γ_{49}

$\Gamma_{72}/\Gamma_{49} = (\Gamma_{73}+0.236\Gamma_{110}+0.888\Gamma_{126})/(0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.4508\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0348±0.0028 OUR FIT				
0.034 ±0.002 ±0.003	668	BORTOLETTO93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau(\text{ex.}K^0,\omega,\eta))/\Gamma_{\rm total}$ — Γ_{73}/Γ

VALUE (%)	DOCUMENT ID
0.11±0.04 OUR FIT	

$\Gamma(h^- h^- h^+ \geq 3\pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{74}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$0.14^{+0.09}_{-0.07}$ OUR FIT Error includes scale factor of 1.5.				
0.11±0.04±0.05	440	BUSKULIC 96	ALEP	LEP 1991–1993 data

$\Gamma(h^- h^- h^+ 3\pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{75}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
2.85±0.56±0.51	57	ANDERSON 97	CLEO	$E^{ee}_{\rm cm}$ = 10.6 GeV

$\Gamma(K^- h^+ h^- \geq \text{0 neutrals } \nu_\tau)/\Gamma_{\rm total}$

$\Gamma_{76}/\Gamma = (0.3431\Gamma_{34}+0.3431\Gamma_{38}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85})/\Gamma$

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
0.54±0.07 OUR FIT Error includes scale factor of 1.1.				
<0.6	90	AIHARA 84C	TPC	$E^{ee}_{\rm cm}$ = 29 GeV

$\Gamma(K^- \pi^+ \pi^- \geq \text{0 neutrals } \nu_\tau)/\Gamma_{\rm total}$

$\Gamma_{77}/\Gamma = (0.3431\Gamma_{34}+0.3431\Gamma_{38}+\Gamma_{79}+\Gamma_{81})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.31 ±0.06 OUR FIT Error includes scale factor of 1.1.					
0.30 ±0.07 OUR AVERAGE Error includes scale factor of 1.2.					
0.275±0.064	avg		[131] BARATE 98	ALEP	1991–1995 LEP runs
0.58 $^{+0.15}_{-0.13}$ ±0.12	f&a	20	[132] BAUER 94	TPC	$E^{ee}_{\rm cm}$ = 29 GeV
0.22 $^{+0.16}_{-0.13}$ ±0.05	f&a	9	[133] MILLS 85	DLCO	$E^{ee}_{\rm cm}$ = 29 GeV

[131] Not independent of BARATE 98 $\Gamma(\tau^- \to K^- \pi^+ \pi^- \nu_\tau)/\Gamma_{\rm total}$ and $\Gamma(\tau^- \to K^- \pi^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$ values.

[132] We multiply 0.58% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

[133] Error correlated with MILLS 85 ($K K \pi \nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(K^- \pi^+ \pi^- \nu_\tau)/\Gamma_{\rm total}$ — $\Gamma_{78}/\Gamma = (0.3431\Gamma_{34}+\Gamma_{79})/\Gamma$

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.23 ±0.04 OUR FIT			
0.214±0.037±0.029	BARATE 98	ALEP	1991–1995 LEP runs

$\Gamma(K^- \pi^+ \pi^- \nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{79}/Γ

VALUE (%)	DOCUMENT ID
0.18±0.05 OUR FIT	

$\Gamma(K^- \pi^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$ — $\Gamma_{80}/\Gamma = (0.3431\Gamma_{38}+\Gamma_{81})/\Gamma$

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.08 ±0.04 OUR FIT			
0.061±0.039±0.018	BARATE 98	ALEP	1991–1995 LEP runs

$\Gamma(K^- \pi^+ \pi^- \pi^0 \nu_\tau(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{81}/Γ

VALUE	DOCUMENT ID
$(2.4^{+4.3}_{-1.6}) \times 10^{-4}$ OUR FIT	

$\Gamma(K^- \pi^+ K^- \geq \text{0 neut. } \nu_\tau)/\Gamma_{\rm total}$ — Γ_{82}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.09	95	BAUER 94	TPC	$E^{ee}_{\rm cm}$ = 29 GeV

$\Gamma(K^- K^+ \pi^- \geq \text{0 neut. } \nu_\tau)/\Gamma_{\rm total}$ — $\Gamma_{83}/\Gamma = (\Gamma_{84}+\Gamma_{85})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.23 ±0.04 OUR FIT					
0.22 ±0.04 OUR AVERAGE					
0.238±0.042	avg		[134] BARATE 98	ALEP	1991–1995 LEP runs
0.15 $^{+0.09}_{-0.07}$ ±0.03	f&a	4	[135] BAUER 94	TPC	$E^{ee}_{\rm cm}$ = 29 GeV

[134] Not independent of BARATE 98 $\Gamma(\tau^- \to K^- K^+ \pi^- \nu_\tau)/\Gamma_{\rm total}$ and $\Gamma(\tau^- \to K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$ values.

[135] We multiply 0.15% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K^- K^+ \pi^- \nu_\tau)/\Gamma_{\rm total}$ — Γ_{84}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.161±0.026 OUR FIT				
0.165±0.027 OUR AVERAGE				
0.163±0.021±0.017		BARATE 98	ALEP	1991–1995 LEP runs
0.22 $^{+0.17}_{-0.11}$ ±0.05	9	[136] MILLS 85	DLCO	$E^{ee}_{\rm cm}$ = 29 GeV

[136] Error correlated with MILLS 85 ($K \pi \pi \pi^0 \nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{85}/Γ

VALUE (%)	DOCUMENT ID		TECN	COMMENT
0.069 ± 0.030 OUR FIT				
$0.075\pm0.029\pm0.015$	BARATE	98	ALEP	1991–1995 LEP runs

$\Gamma(K^- K^+ K^- \geq 0\,\text{neut.}\ \nu_\tau)/\Gamma_{\rm total}$ — Γ_{86}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.21	95	BAUER	94	TPC	$E^{ee}_{\rm cm}= 29$ GeV

$\Gamma(K^- K^+ K^- \nu_\tau)/\Gamma_{\rm total}$ — Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.9\times10^{-4}$	90	BARATE	98	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^+ \pi^- \geq 0\,\text{neut.}\ \nu_\tau)/\Gamma_{\rm total}$ — Γ_{88}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.25	95	BAUER	94	TPC	$E^{ee}_{\rm cm}= 29$ GeV

$\Gamma(e^- e^- e^+ \overline{\nu}_e \nu_\tau)/\Gamma_{\rm total}$ — Γ_{89}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
$2.8\pm1.4\pm0.4$	5	ALAM	96	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV

$\Gamma(\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau)/\Gamma_{\rm total}$ — Γ_{90}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<3.6	90	ALAM	96	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV

$\Gamma(3h^- 2h^+ \geq 0\,\text{neutrals}\ \nu_\tau\,(\text{ex.}\ K^0_S \to \pi^-\pi^+)(\text{“5-prong”}))/\Gamma_{\rm total}$ — Γ_{91}/Γ

$\Gamma_{91}/\Gamma = (\Gamma_{92}+\Gamma_{93})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.097 ± 0.007 OUR FIT					
0.102 ± 0.011 OUR AVERAGE					
$0.097\pm0.005\pm0.011$	419	GIBAUT	94B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV
$0.26\ \pm0.06\ \pm0.05$		ACTON	92H	OPAL	$E^{ee}_{\rm cm}= 88.2$–94.2 GeV
$0.10\ ^{+0.05}_{-0.04}\ \pm0.03$		DECAMP	92C	ALEP	1989–1990 LEP runs
0.102 ± 0.029	13	BYLSMA	87	HRS	$E^{ee}_{\rm cm}= 29$ GeV
$0.16\ \pm0.08\ \pm0.04$	4	BURCHAT	85	MRK2	$E^{ee}_{\rm cm}= 29$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.16\ \pm0.13\ \pm0.04$		BEHREND	89B	CELL	$E^{ee}_{\rm cm}= 14$–47 GeV
$0.3\ \pm0.1\ \pm0.2$		BARTEL	85F	JADE	$E^{ee}_{\rm cm}= 34.6$ GeV
$0.13\ \pm0.04$	10	BELTRAMI	85	HRS	Repl. by BYLSMA 87
$1.0\ \pm0.4$	10	BEHREND	82	CELL	Repl. by BEHREND 89B

$[\Gamma(h^- h^- h^+ \geq 1\,\text{neutrals}\ \nu_\tau) + \Gamma(3h^- 2h^+ \geq 0\,\text{neutrals}\ \nu_\tau\,(\text{ex.}\ K^0_S \to \pi^-\pi^+)(\text{“5-prong”}))]/\Gamma_{\rm total}$ — $(\Gamma_{58}+\Gamma_{91})/\Gamma$

$(\Gamma_{58}+\Gamma_{91})/\Gamma = (0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.1077\Gamma_{41}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{81}+\Gamma_{85}+\Gamma_{92}+\Gamma_{93}+0.285\Gamma_{110}+0.888\Gamma_{125}+0.9101\Gamma_{126})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.28 ± 0.11 OUR FIT Error includes scale factor of 1.2.					
$5.4\ \pm0.5$ OUR AVERAGE					
$5.05\pm0.29\pm0.65$	570	DECAMP	92C	ALEP	1989–1990 LEP runs
$5.8\ \pm0.7\ \pm0.2$	352	[137] BEHREND	90	CELL	$E^{ee}_{\rm cm}= 35$ GeV

[137] BEHREND 90 not independent of their $\Gamma(h^- h^- h^+ \geq 1\,\text{neutrals}\,\nu_\tau)/\Gamma_{\rm total}$ measurement.

$\Gamma(3h^- 2h^+ \nu_\tau\,(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{92}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.075 ± 0.007 OUR FIT					
0.073 ± 0.008 OUR AVERAGE					
$0.080\pm0.011\pm0.013$	58	BUSKULIC	96	ALEP	LEP 1991–1993 data
$0.077\pm0.005\pm0.009$	295	GIBAUT	94B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV
$0.064\pm0.023\pm0.01$	12	ALBRECHT	88B	ARG	$E^{ee}_{\rm cm}= 10$ GeV
0.051 ± 0.020	7	BYLSMA	87	HRS	$E^{ee}_{\rm cm}= 29$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067 ± 0.030	5	[138] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[138] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ \pi^0 \nu_\tau\,(\text{ex.}K^0))/\Gamma_{\rm total}$ — Γ_{93}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.022 ± 0.005 OUR FIT					
0.021 ± 0.005 OUR AVERAGE					
$0.018\pm0.007\pm0.012$	18	BUSKULIC	96	ALEP	LEP 1991–1993 data
$0.019\pm0.004\pm0.004$	31	GIBAUT	94B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV
0.051 ± 0.022	6	BYLSMA	87	HRS	$E^{ee}_{\rm cm}= 29$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067 ± 0.030	5	[139] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[139] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ 2\pi^0 \nu_\tau)/\Gamma_{\rm total}$ — Γ_{94}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	GIBAUT	94B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV

$\Gamma((5\pi)^- \nu_\tau)/\Gamma_{\rm total}$ — Γ_{95}/Γ

$\Gamma_{95}/\Gamma = (\Gamma_{26}+\frac{1}{4}\Gamma_{41}+\Gamma_{73}+\Gamma_{92}+0.236\Gamma_{110}+0.888\Gamma_{126})/\Gamma$

Data marked “avg” are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. “f&a” marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID		TECN	COMMENT
0.74 ± 0.07 OUR FIT					
$0.61\pm0.06\pm0.08$	**avg**	[140] GIBAUT	94B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV

[140] Not independent of GIBAUT 94B B($3h^- 2h^+ \nu_\tau$), PROCARIO 93 B($h^- 4\pi^0 \nu_\tau$), and BORTOLETTO 93 B($2h^- h^+ 2\pi^0 \nu_\tau$)/B(“3prong”) measurements. Result is corrected for η contributions.

$\Gamma(4h^- 3h^+ \geq 0\,\text{neutrals}\ \nu_\tau\,(\text{“7-prong”}))/\Gamma_{\rm total}$ — Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.4\times10^{-6}$	90	EDWARDS	97B	CLEO	$E^{ee}_{\rm cm}= 10.6$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8\times10^{-5}$	95	ACKERSTAFF	97J	OPAL	1990–1995 LEP runs
$<2.9\times10^{-4}$	90	BYLSMA	87	HRS	$E^{ee}_{\rm cm}= 29$ GeV

$\Gamma(K^*(892)^- \geq 0(h^0 \neq K^0_S)\nu_\tau)/\Gamma_{\rm total}$ — Γ_{97}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$1.94\pm0.27\pm0.15$	74	AKERS	94G	OPAL	$E^{ee}_{\rm cm}= 88$–94 GeV

$\Gamma(K^*(892)^- \geq 0\,\text{neutrals}\ \nu_\tau)/\Gamma_{\rm total}$ — Γ_{98}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.33 ± 0.13 OUR AVERAGE					
$1.19\pm0.15^{+0.13}_{-0.18}$	104	ALBRECHT	95H	ARG	$E^{ee}_{\rm cm}= 9.4$–10.6 GeV
$1.43\pm0.11\pm0.13$	475	[141] GOLDBERG	90	CLEO	$E^{ee}_{\rm cm}= 9.4$–10.9 GeV

[141] GOLDBERG 90 estimates that 10% of observed $K^*(892)$ are accompanied by a π^0.

$\Gamma(K^*(892)^- \nu_\tau)/\Gamma_{\rm total}$ — Γ_{99}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.28 ± 0.08 OUR AVERAGE					
$1.39\pm0.09\pm0.10$		[142] BUSKULIC	96	ALEP	LEP 1991–1993 data
1.11 ± 0.12		[143] COAN	96	CLEO	$E^{ee}_{\rm cm} \approx 10.6$ GeV
$1.42\pm0.22\pm0.09$		[144] ACCIARRI	95F	L3	1991–1993 LEP runs
$1.23\pm0.21^{+0.11}_{-0.21}$	54	[145] ALBRECHT	88L	ARG	$E^{ee}_{\rm cm}= 10$ GeV
$1.9\ \pm0.3\ \pm0.4$	44	[146] TSCHIRHART	88	HRS	$E^{ee}_{\rm cm}= 29$ GeV
$1.5\ \pm0.4\ \pm0.4$	15	[147] AIHARA	87C	TPC	$E^{ee}_{\rm cm}= 29$ GeV
$1.3\ \pm0.3\ \pm0.3$	31	YELTON	86	MRK2	$E^{ee}_{\rm cm}= 29$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.45\pm0.13\pm0.11$	273	[148] BUSKULIC	94F	ALEP	Repl. by BUSKULIC 96
$1.7\ \pm0.7$	11	DORFAN	81	MRK2	$E^{ee}_{\rm cm}= 4.2$–6.7 GeV

[142] Not independent of BUSKULIC 96 B($\pi^- \overline{K}^0 \nu_\tau$) and B($K^- \pi^0 \nu_\tau$) measurements.

[143] Not independent of COAN 96 B($\pi^- \overline{K}^0 \nu_\tau$) and BATTLE 94 B($K^- \pi^0 \nu_\tau$) measurements. $K\pi$ final states are consistent with and assumed to originate from $K^*(892)^-$ production.

[144] This result is obtained from their B($\pi^- \overline{K}^0 \nu_\tau$) assuming all those decays originate in $K^*(892)^-$ decays.

[145] The authors divide by $\Gamma_1/\Gamma = 0.865$ to obtain this result.

[146] Not independent of TSCHIRHART 88 $\Gamma(\tau^- \to h^- \overline{K}^0 \geq 0\,\text{neutrals} \geq 0K^0_L \nu_\tau)/\Gamma(\text{total})$.

[147] Decay π^- identified in this experiment, is assumed in the others.

[148] BUSKULIC 94F obtain this result from BUSKULIC 94F B($\overline{K}^0 \pi^- \nu_\tau$) and BUSKULIC 94E B($K^- \pi^0 \nu_\tau$) assuming all of those decays originate in $K^*(892)^-$ decays.

$\Gamma(K^*(892)^- \nu_\tau)/\Gamma(\pi^- \pi^0 \nu_\tau)$ — Γ_{99}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.075 ± 0.027	[149] ABREU	94K	DLPH	LEP 1992 Z data

[149] ABREU 94K quote $B(\tau^- \to K^*(892)^- \nu_\tau) B(K^*(892)^- \to K^- \pi^0)/B(\tau^- \to \rho^- \nu_\tau) = 0.025 \pm 0.009$. We divide by $B(K^*(892)^- \to K^- \pi^0) = 0.333$ to obtain this result.

$\Gamma(K^*(892)^0 K^- \geq 0\,\text{neutrals}\ \nu_\tau)/\Gamma_{\rm total}$ — Γ_{100}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.32\pm0.08\pm0.12$	119	GOLDBERG	90	CLEO	$E^{ee}_{\rm cm}= 9.4$–10.9 GeV

$\Gamma(K^*(892)^0 K^- \nu_\tau)/\Gamma_{\rm total}$ — Γ_{101}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.21\ \pm0.04$ OUR AVERAGE					
0.213 ± 0.048		[150] BARATE	98	ALEP	1991–1995 LEP runs
$0.20\ \pm0.05\ \pm0.04$	47	ALBRECHT	95H	ARG	$E^{ee}_{\rm cm}= 9.4$–10.6 GeV

[150] BARATE 98 measure the K^- ($\rho^0 \to \pi^+\pi^-$) fraction in $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ decays to be (35 ± 11)% and derive this result from their measurement of $\Gamma(\tau^- \to K^-\pi^+\pi^-\nu_\tau)/\Gamma_{\rm total}$ assuming the intermediate states are all $K^-\rho$ and $K^- K^*(892)^0$.

$\Gamma(\overline{K}^*(892)^0 \pi^- \geq 0\,\text{neutrals}\ \nu_\tau)/\Gamma_{\rm total}$ — Γ_{102}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.38\pm0.11\pm0.13$	105	GOLDBERG	90	CLEO	$E^{ee}_{\rm cm}= 9.4$–10.9 GeV

$\Gamma(\overline{K}^*(892)^0\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{103}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.22 ±0.05 OUR AVERAGE				
0.209±0.058		[151] BARATE 98	ALEP	1991–1995 LEP runs
0.25 ±0.10 ±0.05	27	ALBRECHT 95H	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[151] BARATE 98 measure the $K^-K^*(892)^0$ fraction in $\tau^- \to K^-K^+\pi^-\nu_\tau$ decays to be (87 ± 13)% and derive this result from their measurement of $\Gamma(\tau^- \to K^-K^+\pi^-\nu_\tau)/\Gamma_{\rm total}$.

$\Gamma((\overline{K}^*(892)\pi)^-\nu_\tau \to \pi^-\overline{K}^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{104}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.106±0.037±0.032	[152] BARATE 98E	ALEP	1991–1995 LEP runs

[152] BARATE 98E determine the $\overline{K}^0\rho^-$ fraction in $\tau^- \to \pi^-\overline{K}^0\pi^0\nu_\tau$ decays to be (0.64 ± 0.09 ± 0.10) and multiply their $B(\pi^-\overline{K}^0\pi^0\nu_\tau)$ measurement by one minus this fraction to obtain the quoted result.

$\Gamma(K_1(1270)^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{105}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$0.41^{+0.41}_{-0.35}\pm0.10$	5	[153] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[153] We multiply 0.41% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K_1(1400)^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{106}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$0.76^{+0.40}_{-0.33}\pm0.20$	11	[154] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[154] We multiply 0.76% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$[\Gamma(K_1(1270)^-\nu_\tau)+\Gamma(K_1(1400)^-\nu_\tau)]/\Gamma_{\rm total}$ $(\Gamma_{105}+\Gamma_{106})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$1.17^{+0.41}_{-0.37}\pm0.29$	16	[155] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[155] We multiply 1.17% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error. Not independent of BAUER 94 $B(K_1(1270)^-\nu_\tau)$ and BAUER 94 $B(K_1(1400)^-\nu_\tau)$ measurements.

$\Gamma(K_2^*(1430)^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{107}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.3	95		TSCHIRHART 88	HRS	$E^{ee}_{\rm cm}$= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.33	95		[156] ACCIARRI 95F	L3	1991–1993 LEP runs
<0.9	95	0	DORFAN 81	MRK2	$E^{ee}_{\rm cm}$= 4.2–6.7 GeV

[156] ACCIARRI 95F quote $B(\tau^- \to K^*(1430)^- \to \pi^-\overline{K}^0\nu_\tau) < 0.11\%$. We divide by $B(K^*(1430)^- \to \pi^-\overline{K}^0) = 0.33$ to obtain the limit shown.

$\Gamma(a_0(980)^- \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{\rm total} \times B(a_0(980) \to K^0K^-)$ $\Gamma_{108}/\Gamma \times B$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-4}$	90	GOLDBERG 90	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.9 GeV

$\Gamma(\eta\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{109}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.4	95	0	BARTELT 96	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.2	95		BUSKULIC 97C	ALEP	1991–1994 LEP runs
< 3.4	95		ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
< 90	95		ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV
<140	90		BEHREND 88	CELL	$E^{ee}_{\rm cm}$= 14–46.8 GeV
<180	95		BARINGER 87	CLEO	$E^{ee}_{\rm cm}$= 10.5 GeV
<250	90	0	COFFMAN 87	MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV
510 ±100±120		65	DERRICK 87	HRS	$E^{ee}_{\rm cm}$= 29 GeV
<100	95		GAN 87B	MRK2	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(\eta\pi^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{110}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.174±0.024 OUR FIT					
0.173±0.024 OUR AVERAGE					
0.18 ±0.04 ±0.02			BUSKULIC 97C	ALEP	1991–1994 LEP runs
0.17 ±0.02 ±0.02		125	ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.10	95		ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV
<2.10	95		BARINGER 87	CLEO	$E^{ee}_{\rm cm}$= 10.5 GeV
$4.20^{+0.70}_{-1.20}$ ±1.60			[157] GAN 87	MRK2	$E^{ee}_{\rm cm}$= 29 GeV

[157] Highly correlated with GAN 87 $\Gamma(\pi^-3\pi^0\nu_\tau)/\Gamma(\text{total})$ value.

$\Gamma(\eta\pi^-\pi^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{111}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
1.4±0.6±0.3		15	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.3	95		ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
<120	95		ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV

$\Gamma(\eta K^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{112}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
2.7±0.6 OUR AVERAGE					
$2.9^{+1.3}_{-1.2}\pm0.7$			BUSKULIC 97C	ALEP	1991–1994 LEP runs
2.6±0.5±0.5		85	BARTELT 96	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.7	95		ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV

$\Gamma(\eta\pi^+\pi^-\pi^- \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{\rm total}$ Γ_{113}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.3	90	ABACHI 87B	HRS	$E^{ee}_{\rm cm}$= 29 GeV

$\Gamma(\eta\pi^-\pi^+\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{114}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
$3.4^{+0.6}_{-0.5}\pm0.6$	89	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\eta a_1(1260)^-\nu_\tau \to \eta\pi^-\rho^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{115}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-4}$	90	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\eta\eta\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{116}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
< 1.1	95	ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<83	95	ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV

$\Gamma(\eta\eta\pi^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{117}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
< 2.0	95	ARTUSO 92	CLEO	$E^{ee}_{\rm cm}$ ≈ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<90	95	ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV

$\Gamma(\eta'(958)\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{118}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.4 \times 10^{-5}$	90	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\eta'(958)\pi^-\pi^0\nu_\tau)/\Gamma_{\rm total}$ Γ_{119}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.0 \times 10^{-5}$	90	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\phi\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{120}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.0 \times 10^{-4}$	90	[158] AVERY 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.5 \times 10^{-4}$	90	ALBRECHT 95H	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[158] AVERY 97 limit varies from (1.2–2.0) × 10^{-4} depending on decay model assumptions.

$\Gamma(\phi K^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{121}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.7 \times 10^{-5}$	90	[159] AVERY 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

[159] AVERY 97 limit varies from (5.4–6.7) × 10^{-5} depending on decay model assumptions.

$\Gamma(f_1(1285)\pi^-\nu_\tau)/\Gamma_{\rm total}$ Γ_{122}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
$5.8^{+1.4}_{-1.3}\pm1.8$	54	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(f_1(1285)\pi^-\nu_\tau \to \eta\pi^-\pi^+\pi^-\nu_\tau)/\Gamma(\eta\pi^-\pi^+\pi^-\nu_\tau)$ $\Gamma_{123}/\Gamma_{114}$

VALUE	DOCUMENT ID	TECN	COMMENT
0.55±0.14	BERGFELD 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(h^-\omega \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{\rm total}$ Γ_{124}/Γ

$\Gamma_{124}/\Gamma = (\Gamma_{125}+\Gamma_{126})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
2.36±0.08 OUR FIT					
1.65±0.3 ±0.2	**avg**	1513	ALBRECHT 88M	ARG	$E^{ee}_{\rm cm}$ ≈ 10 GeV

$\Gamma(h^- \omega \nu_\tau)/\Gamma_{\text{total}}$ Γ_{125}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.93±0.06 OUR FIT					
1.92±0.07 OUR AVERAGE					
1.91±0.07±0.06	f&a	5803	BUSKULIC 97C	ALEP	1991–1994 LEP runs
1.95±0.07±0.11	avg	2223	[160] BALEST 95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
1.60±0.27±0.41	f&a	139	BARINGER 87	CLEO	E^{ee}_{cm}= 10.5 GeV

[160] Not independent of BALEST 95C $B(\tau^- \to h^- \omega \nu_\tau)/B(\tau^- \to h^- h^- h^+ \pi^0 \nu_\tau)$ value.

$[\Gamma(h^- \rho \pi^0 \nu_\tau) + \Gamma(h^- \rho^+ h^- \nu_\tau) + \Gamma(h^- \rho^- h^+ \nu_\tau) + \Gamma(h^- \omega \nu_\tau)]/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ $(\Gamma_{68}+\Gamma_{69}+\Gamma_{70}+\Gamma_{125})/\Gamma_{60}$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
>0.81	95	[161] ALBRECHT 91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[161] ALBRECHT 91D not independent of their $\Gamma(h^- \omega \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex.}K^0))$, $\Gamma(h^- \rho \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, and $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma(h^- \omega \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex.}K^0))$ Γ_{125}/Γ_{61}

$\Gamma_{125}/\Gamma_{61} = \Gamma_{125}/(\Gamma_{65}+\Gamma_{81}+\Gamma_{85}+0.888\Gamma_{125}+0.0221\Gamma_{126})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.448±0.015 OUR FIT				
0.453±0.019 OUR AVERAGE				
0.431±0.033	2350	[162] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.464±0.016±0.017	2223	[163] BALEST 95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.37 ±0.05 ±0.02	458	[164] ALBRECHT 91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[162] BUSKULIC 96 quote the fraction of $\tau \to h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0) decays which originate in a $h^- \omega$ final state = 0.383 ± 0.029. We divide this by the $\omega(782) \to \pi^+ \pi^- \pi^0$ branching fraction (0.888).

[163] BALEST 95C quote the fraction of $\tau^- \to h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0) decays which originate in a $h^- \omega$ final state equals 0.412 ± 0.014 ± 0.015. We divide this by the $\omega(782) \to \pi^+ \pi^- \pi^0$ branching fraction (0.888).

[164] ALBRECHT 91D quote the fraction of $\tau^- \to h^- h^- h^+ \pi^0 \nu_\tau$ decays which originate in a $\pi^- \omega$ final state equals 0.33 ± 0.04 ± 0.02. We divide this by the $\omega(782) \to \pi^+ \pi^- \pi^0$ branching fraction (0.888).

$\Gamma(h^- \omega \pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{126}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.43±0.06 OUR FIT				
0.43±0.06±0.05	7283	BUSKULIC 97C	ALEP	1991–1994 LEP runs

$\Gamma(h^- \omega 2\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{127}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
$1.89^{+0.74}_{-0.67}$±0.40	19	ANDERSON 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(h^- \omega \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \geq 0\text{neut.}\ \nu_\tau (\text{"3-prong"}))$ Γ_{126}/Γ_{49}

$\Gamma_{126}/\Gamma_{49} = \Gamma_{126}/(0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{36}+0.3431\Gamma_{38}+0.4508\Gamma_{41}+\Gamma_{57}+\Gamma_{65}+\Gamma_{73}+\Gamma_{74}+\Gamma_{79}+\Gamma_{81}+\Gamma_{84}+\Gamma_{85}+0.285\Gamma_{110}+0.9101\Gamma_{125}+0.9101\Gamma_{126})$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID	TECN	COMMENT
0.0283±0.0031 OUR FIT					
0.028 ±0.003 ±0.003	**avg**	430	[165] BORTOLETTO93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[165] Not independent of BORTOLETTO 93 $\Gamma(\tau^- \to h^- \omega \pi^0 \nu_\tau)/\Gamma(\tau^- \to h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.}K^0))$ value.

$\Gamma(h^- \omega \pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.}K^0))$ Γ_{126}/Γ_{72}

$\Gamma_{126}/\Gamma_{72} = \Gamma_{126}/(\Gamma_{73}+0.236\Gamma_{110}+0.888\Gamma_{126})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.81±0.08 OUR FIT			
0.81±0.06±0.06	BORTOLETTO93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(e^- \gamma)/\Gamma_{\text{total}}$ Γ_{128}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.7 x 10^{-6}	90	EDWARDS 97	CLEO	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.1 x 10^{-4}	90	ABREU 95U	DLPH	1990–1993 LEP runs
<1.2 x 10^{-4}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<2.0 x 10^{-4}	90	KEH 88	CBAL	E^{ee}_{cm}= 10 GeV
<6.4 x 10^{-4}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^- \gamma)/\Gamma_{\text{total}}$ Γ_{129}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 3.0 x 10^{-6}	90	EDWARDS 97	CLEO	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 6.2 x 10^{-5}	90	ABREU 95U	DLPH	1990–1993 LEP runs
< 0.42 x 10^{-5}	90	BEAN 93	CLEO	E^{ee}_{cm}= 10.6 GeV
< 3.4 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<55 x 10^{-5}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- \pi^0)/\Gamma_{\text{total}}$ Γ_{130}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 3.7 x 10^{-6}	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 17 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
< 14 x 10^{-5}	90	KEH 88	CBAL	E^{ee}_{cm}= 10 GeV
<210 x 10^{-5}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^- \pi^0)/\Gamma_{\text{total}}$ Γ_{131}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 4.0 x 10^{-6}	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 4.4 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<82 x 10^{-5}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- K^0)/\Gamma_{\text{total}}$ Γ_{132}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 x 10^{-3}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^- K^0)/\Gamma_{\text{total}}$ Γ_{133}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.0 x 10^{-3}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- \eta)/\Gamma_{\text{total}}$ Γ_{134}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 8.2 x 10^{-6}	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 6.3 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<24 x 10^{-5}	90	KEH 88	CBAL	E^{ee}_{cm}= 10 GeV

$\Gamma(\mu^- \eta)/\Gamma_{\text{total}}$ Γ_{135}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<9.6 x 10^{-6}	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.3 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(e^- \rho^0)/\Gamma_{\text{total}}$ Γ_{136}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 2.0 x 10^{-6}	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 0.42 x 10^{-5}	90	[166] BARTELT 94	CLEO	Repl. by BLISS 98
< 1.9 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<37 x 10^{-5}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[166] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \rho^0)/\Gamma_{\text{total}}$ Γ_{137}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 6.3 x 10^{-6}	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 0.57 x 10^{-5}	90	[167] BARTELT 94	CLEO	Repl. by BLISS 98
< 2.9 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
<44 x 10^{-5}	90	HAYES 82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[167] BARTELT 94 assume phase space decays.

$\Gamma(e^- K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{138}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.1 x 10^{-6}	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.63 x 10^{-5}	90	[168] BARTELT 94	CLEO	Repl. by BLISS 98
<3.8 x 10^{-5}	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV

[168] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- K^*(892)^0)/\Gamma_{\rm total}$ Γ_{139}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.5\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.94\times10^{-5}$	90	[169] BARTELT	94	CLEO	Repl. by BLISS 98
$<4.5\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

[169] BARTELT 94 assume phase space decays.

$\Gamma(e^- \overline{K}^*(892)^0)/\Gamma_{\rm total}$ Γ_{140}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.4\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1\times10^{-5}$	90	[170] BARTELT	94	CLEO	Repl. by BLISS 98

[170] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \overline{K}^*(892)^0)/\Gamma_{\rm total}$ Γ_{141}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.5\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.87\times10^{-5}$	90	[171] BARTELT	94	CLEO	Repl. by BLISS 98

[171] BARTELT 94 assume phase space decays.

$\Gamma(e^- \phi)/\Gamma_{\rm total}$ Γ_{142}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.9\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^- \phi)/\Gamma_{\rm total}$ Γ_{143}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.0\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\pi^- \gamma)/\Gamma_{\rm total}$ Γ_{144}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<28\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(\pi^- \pi^0)/\Gamma_{\rm total}$ Γ_{145}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<37\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(e^- e^+ e^-)/\Gamma_{\rm total}$ Γ_{146}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.9\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.33\times10^{-5}$	90	[172] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.3\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<2.7\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9
$<40\times10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{\rm cm}$= 3.8–6.8 GeV

[172] BARTELT 94 assume phase space decays.

$\Gamma(e^- \mu^+ \mu^-)/\Gamma_{\rm total}$ Γ_{147}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.8\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.36\times10^{-5}$	90	[173] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.9\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<2.7\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9
$<33\times10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{\rm cm}$= 3.8–6.8 GeV

[173] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \mu^- \mu^-)/\Gamma_{\rm total}$ Γ_{148}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.35\times10^{-5}$	90	[174] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.8\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<1.6\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[174] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- e^+ e^-)/\Gamma_{\rm total}$ Γ_{149}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.7\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.34\times10^{-5}$	90	[175] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.4\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<2.7\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9
$<44\times10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{\rm cm}$= 3.8–6.8 GeV

[175] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+ e^- e^-)/\Gamma_{\rm total}$ Γ_{150}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.34\times10^{-5}$	90	[176] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.4\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<1.6\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[176] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \mu^+ \mu^-)/\Gamma_{\rm total}$ Γ_{151}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.9\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.43\times10^{-5}$	90	[177] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.9\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<1.7\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9
$<49\times10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{\rm cm}$= 3.8–6.8 GeV

[177] BARTELT 94 assume phase space decays.

$\Gamma(e^- \pi^+ \pi^-)/\Gamma_{\rm total}$ Γ_{152}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.2\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.44\times10^{-5}$	90	[178] BARTELT	94	CLEO	Repl. by BLISS 98
$<2.7\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<6.0\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[178] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \pi^- \pi^-)/\Gamma_{\rm total}$ Γ_{153}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.9\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.44\times10^{-5}$	90	[179] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.8\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<1.7\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[179] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \pi^+ \pi^-)/\Gamma_{\rm total}$ Γ_{154}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.2\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.74\times10^{-5}$	90	[180] BARTELT	94	CLEO	Repl. by BLISS 98
$<3.6\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<3.9\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[180] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+ \pi^- \pi^-)/\Gamma_{\rm total}$ Γ_{155}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.69\times10^{-5}$	90	[181] BARTELT	94	CLEO	Repl. by BLISS 98
$<6.3\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<3.9\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[181] BARTELT 94 assume phase space decays.

$\Gamma(e^- \pi^+ K^-)/\Gamma_{\rm total}$ Γ_{156}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.4\times10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.77\times10^{-5}$	90	[182] BARTELT	94	CLEO	Repl. by BLISS 98
$<2.9\times10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<5.8\times10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[182] BARTELT 94 assume phase space decays.

$\Gamma(e^-\pi^-K^+)/\Gamma_{\text{total}}$ Γ_{157}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.8 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.46 \times 10^{-5}$	90	[183] BARTELT	94	CLEO	Repl. by BLISS 98
$<5.8 \times 10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[183] BARTELT 94 assume phase space decays.

$\Gamma(e^+\pi^-K^-)/\Gamma_{\text{total}}$ Γ_{158}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.1 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.45 \times 10^{-5}$	90	[184] BARTELT	94	CLEO	Repl. by BLISS 98
$<2.0 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<4.9 \times 10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[184] BARTELT 94 assume phase space decays.

$\Gamma(e^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{159}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.0 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(e^+K^-K^-)/\Gamma_{\text{total}}$ Γ_{160}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.8 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^-\pi^+K^-)/\Gamma_{\text{total}}$ Γ_{161}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 7.5 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.87 \times 10^{-5}$	90	[185] BARTELT	94	CLEO	Repl. by BLISS 98
$<11 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$< 7.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[185] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\pi^-K^+)/\Gamma_{\text{total}}$ Γ_{162}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.4 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-5}$	90	[186] BARTELT	94	CLEO	Repl. by BLISS 98
$<7.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[186] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+\pi^-K^-)/\Gamma_{\text{total}}$ Γ_{163}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.0 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.0 \times 10^{-5}$	90	[187] BARTELT	94	CLEO	Repl. by BLISS 98
$<5.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
$<4.0 \times 10^{-5}$	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[187] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{164}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<15 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^+K^-K^-)/\Gamma_{\text{total}}$ Γ_{165}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.0 \times 10^{-6}$	90	BLISS	98	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(e^-\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{166}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.5 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^-\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{167}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<14 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(e^-\eta\eta)/\Gamma_{\text{total}}$ Γ_{168}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<35 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^-\eta\eta)/\Gamma_{\text{total}}$ Γ_{169}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<60 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(e^-\pi^0\eta)/\Gamma_{\text{total}}$ Γ_{170}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<24 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\mu^-\pi^0\eta)/\Gamma_{\text{total}}$ Γ_{171}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<22 \times 10^{-6}$	90	BONVICINI	97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

$\Gamma(\bar{p}\gamma)/\Gamma_{\text{total}}$ Γ_{172}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<29 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(\bar{p}\pi^0)/\Gamma_{\text{total}}$ Γ_{173}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<66 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(\bar{p}\eta)/\Gamma_{\text{total}}$ Γ_{174}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<130 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(e^-\,\text{light boson})/\Gamma(e^-\bar{\nu}_e\nu_\tau)$ Γ_{175}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	95	[188] ALBRECHT	95G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.018	95	[189] ALBRECHT	90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
<0.040	95	[190] BALTRUSAIT...85		MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV

[188] ALBRECHT 95G limit holds for bosons with mass < 0.4 GeV. The limit rises to 0.036 for a mass of 1.0 GeV, then falls to 0.006 at the upper mass limit of 1.6 GeV.

[189] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.050 for mass = 500 MeV.

[190] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

$\Gamma(\mu^-\,\text{light boson})/\Gamma(e^-\bar{\nu}_e\nu_\tau)$ Γ_{176}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.026	95	[191] ALBRECHT	95G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.033	95	[192] ALBRECHT	90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
<0.125	95	[193] BALTRUSAIT...85		MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV

[191] ALBRECHT 95G limit holds for bosons with mass < 1.3 GeV. The limit rises to 0.034 for a mass of 1.4 GeV, then falls to 0.003 at the upper mass limit of 1.6 GeV.

[192] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.071 for mass = 500 MeV.

[193] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

τ-DECAY PARAMETERS

Written April 1996 by D.E. Groom (LBNL).

Neglecting radiative corrections and terms proportional to m_ℓ^2/m_τ^2, the energy spectrum of the charged decay lepton ℓ in the τ rest frame is given by

$$\begin{aligned}\frac{d^2\Gamma_{\tau\to\ell\nu\bar\nu}}{d\Omega\,dx} &\propto x^2\\ &\times\left\{12(1-x)+\rho_\tau\left(\frac{32}{3}x-8\right)+24\eta_\tau\,\frac{m_\ell}{m_\tau}\,\frac{(1-x)}{x}\right.\\ &\left.-P_\tau\,\xi_\tau\cos\theta\left[4(1-x)+\delta_\tau\left(\frac{32}{3}x-8\right)\right]\right\}.\end{aligned}\tag{1}$$

Here $x = 2E_\ell/m_\tau$ is the scaled lepton energy, P_τ is the τ polarization, and θ is the angle between the τ spin and the lepton momentum. With unpolarized τ's or integrating over the full θ range, the spectrum depends only on ρ_τ and η_τ. Measurements of the other two Michel parameters, ξ_τ and δ_τ, require polarized τ's. The Standard Model predicitions for

ρ_τ, η_τ, ξ_τ and δ_τ are $\frac{3}{4}$, 0, 1 and $\frac{3}{4}$. Where possible, we give separately the parameters for $\tau^- \to e^- \nu_\tau \overline{\nu}_e$ and $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$, to avoid assumptions about universality. Listings labelled "(e or μ)" contain either the results assuming lepton universality if quoted by the experiments or repeat the results from the "e" or "μ" section.

Hadronic two-body decays $\tau \to \nu_\tau h$, $h = \pi, \rho, a_1, \ldots$, can under minimal assumptions be written

$$\frac{1}{\Gamma}\frac{d\Gamma}{dz} = f_h(z) + P_\tau \, \xi_h \, g_h(z) \; , \tag{2}$$

where the kinematic functions f_h, g_h and the definition of the variable z depend on the spin of the hadron h. For the simple case $h = \pi$, one has $z = E_\pi / E_\tau$, $f(z) = 1$, and $g(z) = 2z - 1$. The parameter ξ_h is predicted to be unity and can be identified with twice the negative ν_τ helicity. Again ξ_h is listed, when available, separately for each hadron and averaged over all hadronic decays modes.

ρ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.748±0.010 OUR AVERAGE				
0.72 ±0.09 ±0.03		[194] ABE	97O SLD	1993–1995 SLC runs
0.747±0.010±0.006	55k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.794±0.039±0.031	18k	ACCIARRI	96H L3	1991–1993 LEP runs
0.738±0.038		[195] ALBRECHT	95C ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.751±0.039±0.022		BUSKULIC	95D ALEP	1990–1992 LEP runs
0.79 ±0.10 ±0.10	3732	FORD	87B MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.71 ±0.09 ±0.03	1426	BEHRENDS	85 CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.735±0.013±0.008	31k	AMMAR	97B CLEO	Repl. by ALEXANDER 97F
0.732±0.034±0.020	8.2k	[196] ALBRECHT	95 ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.742±0.035±0.020	8000	ALBRECHT	90E ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[194] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a ρ^τ value of $0.69 \pm 0.13 \pm 0.05$.

[195] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.

[196] Value is from a simultaneous fit for the ρ^τ and η^τ decay parameters to the lepton energy spectrum. Not independent of ALBRECHT 90E ρ^τ(e or μ) value which assumes η^τ=0. Result is strongly correlated with ALBRECHT 95C.

ρ^τ(e) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.745±0.012 OUR AVERAGE				
0.71 ±0.14 ±0.05		ABE	97O SLD	1993–1995 SLC runs
0.747±0.012±0.004	34k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.735±0.036±0.020	4.7k	[197] ALBRECHT	95 ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.793±0.050±0.025		BUSKULIC	95D ALEP	1990–1992 LEP runs
0.79 ±0.08 ±0.06	3230	[198] ALBRECHT	93G ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.64 ±0.06 ±0.07	2753	JANSSEN	89 CBAL	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.62 ±0.17 ±0.14	1823	FORD	87B MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.60 ±0.13	699	BEHRENDS	85 CLEO	e^+e^- near $\Upsilon(4S)$
0.72 ±0.10 ±0.11	594	BACINO	79B DLCO	$E^{ee}_{\rm cm}$= 3.5–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.732±0.014±0.009	19k	AMMAR	97B CLEO	Repl. by ALEXANDER 97F
0.747±0.045±0.028	5106	ALBRECHT	90E ARG	Repl. by ALBRECHT 95

[197] ALBRECHT 95 use tau pair events of the type $\tau^-\tau^+ \to (\ell^- \overline{\nu}_\ell \nu_\tau)(h^+ h^- h^+ (\pi^0) \overline{\nu}_\tau)$ and their charged conjugates.

[198] ALBRECHT 93G use tau pair events of the type $\tau^-\tau^+ \to (\mu^- \overline{\nu}_\mu \nu_\tau)(e^+ \nu_e \overline{\nu}_\tau)$ and their charged conjugates.

ρ^τ(μ) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.741±0.030 OUR AVERAGE				
0.54 ±0.28 ±0.14		ABE	97O SLD	1993–1995 SLC runs
0.750±0.017±0.045	22k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.693±0.057±0.028		BUSKULIC	95D ALEP	1990–1992 LEP runs
0.76 ±0.07 ±0.08	3230	ALBRECHT	93G ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.734±0.055±0.027	3041	ALBRECHT	90E ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.89 ±0.14 ±0.08	1909	FORD	87B MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.81 ±0.13	727	BEHRENDS	85 CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.747±0.048±0.044	13k	AMMAR	97B CLEO	Repl. by ALEXANDER 97F

ξ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.01 ±0.04 OUR AVERAGE				
1.05 ±0.35 ±0.04		[199] ABE	97O SLD	1993–1995 SLC runs
1.007±0.040±0.015	55k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.94 ±0.21 ±0.07	18k	ACCIARRI	96H L3	1991–1993 LEP runs
0.97 ±0.14		[200] ALBRECHT	95C ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
1.18 ±0.15 ±0.16		BUSKULIC	95D ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.90 ±0.15 ±0.10	3230	[201] ALBRECHT	93G ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[199] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a ξ^τ value of $1.02 \pm 0.36 \pm 0.05$.

[200] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^- \overline{\nu}_\ell \nu_\tau)(h^+ h^- h^+ \overline{\nu}_\tau)$ and their charged conjugates.

[201] ALBRECHT 93G measurement determines $|\xi^\tau|$ for the case $\xi^\tau(e) = \xi^\tau(\mu)$, but the authors point out that other LEP experiments determine the sign to be positive.

ξ^τ(e) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.98 ±0.05 OUR AVERAGE				
1.16 ±0.52 ±0.06		ABE	97O SLD	1993–1995 SLC runs
0.979±0.048±0.016	34k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1.03 ±0.23 ±0.09		BUSKULIC	95D ALEP	1990–1992 LEP runs

ξ^τ(μ) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.07 ±0.08 OUR AVERAGE				
0.75 ±0.50 ±0.14		ABE	97O SLD	1993–1995 SLC runs
1.054±0.069±0.047	22k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1.23 ±0.22 ±0.10		BUSKULIC	95D ALEP	1990–1992 LEP runs

η^τ(e or μ) PARAMETER

($V-A$) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.01 ±0.07 OUR AVERAGE				
−0.13 ±0.47 ±0.15		ABE	97O SLD	1993–1995 SLC runs
−0.015±0.061±0.062	31k	AMMAR	97B CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.25 ±0.17 ±0.11	18k	ACCIARRI	96H L3	1991–1993 LEP runs
0.03 ±0.18 ±0.12	8.2k	ALBRECHT	95 ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
−0.04 ±0.15 ±0.11		BUSKULIC	95D ALEP	1990–1992 LEP runs

η^τ(μ) PARAMETER

($V-A$) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.10 ±0.18 OUR AVERAGE				
−0.59 ±0.82 ±0.45		[202] ABE	97O SLD	1993–1995 SLC runs
0.010±0.149±0.171	13k	[203] AMMAR	97B CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
−0.24 ±0.23 ±0.18		BUSKULIC	95D ALEP	1990–1992 LEP runs

[202] Highly correlated (corr. = 0.92) with ABE 97O $\rho^\tau(\mu)$ measurement.

[203] Highly correlated (corr. = 0.949) with AMMAR 97B $\rho^\tau(\mu)$ value.

$(\delta\xi)^\tau$(e or μ) PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.749±0.026 OUR AVERAGE				
0.88 ±0.27 ±0.04		[204] ABE	97O SLD	1993–1995 SLC runs
0.745±0.026±0.009	55k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.81 ±0.14 ±0.06	18k	ACCIARRI	96H L3	1991–1993 LEP runs
0.65 ±0.12		[205] ALBRECHT	95C ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.88 ±0.11 ±0.07		BUSKULIC	95D ALEP	1990–1992 LEP runs

[204] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a $(\rho\xi)^\tau$ value of $0.87 \pm 0.27 \pm 0.04$.

[205] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^- \overline{\nu}_\ell \nu_\tau)(h^+ h^- h^+ \overline{\nu}_\tau)$ and their charged conjugates.

$(\delta\xi)^\tau$(e) PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.733±0.033 OUR AVERAGE				
0.85 ±0.43 ±0.08		ABE	97O SLD	1993–1995 SLC runs
0.720±0.032±0.010	34k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1.11 ±0.17 ±0.07		BUSKULIC	95D ALEP	1990–1992 LEP runs

$(\delta\xi)^\tau$(μ) PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78 ±0.05 OUR AVERAGE				
0.82 ±0.32 ±0.07		ABE	97O SLD	1993–1995 SLC runs
0.786±0.041±0.032	22k	ALEXANDER	97F CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.71 ±0.14 ±0.06		BUSKULIC	95D ALEP	1990–1992 LEP runs

$\xi^\tau(\pi)$ PARAMETER

(V−A) theory predicts $\xi^\tau(\pi) = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.99 ±0.05 OUR AVERAGE				
0.81 ±0.17 ±0.02		ABE 97O	SLD	1993–1995 SLC runs
1.03 ±0.06 ±0.04	2.0k	COAN 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.987±0.057±0.027		BUSKULIC 95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.95 ±0.11 ±0.05		[206] BUSKULIC 94D	ALEP	1990+1991 LEP run

[206] Superseded by BUSKULIC 95D.

$\xi^\tau(\rho)$ PARAMETER

(V−A) theory predicts $\xi^\tau(\rho) = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.996±0.010 OUR AVERAGE				
0.99 ±0.12 ±0.04		ABE 97O	SLD	1993–1995 SLC runs
0.995±0.010±0.003	66k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1.045±0.058±0.032		BUSKULIC 95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.03 ±0.11 ±0.05		[207] BUSKULIC 94D	ALEP	1990+1991 LEP run

[207] Superseded by BUSKULIC 95D.

$\xi^\tau(a_1)$ PARAMETER

(V−A) theory predicts $\xi^\tau(a_1) = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.02 ±0.04 OUR AVERAGE				
1.29 ±0.26 ±0.11	7.4k	[208] ACKERSTAFF 97R	OPAL	1992–1994 LEP runs
1.017±0.039		ALBRECHT 95C	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.937±0.116±0.064		BUSKULIC 95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.08\ {}^{+0.46}_{-0.41}\ {}^{+0.14}_{-0.25}$	2.6k	[209] AKERS 95P	OPAL	Repl. by ACKERSTAFF 97R
1.022±0.028±0.030	1.7k	[210] ALBRECHT 94E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
$1.25\ \pm0.23\ {}^{+0.15}_{-0.08}$	7.5k	ALBRECHT 93C	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[208] ACKERSTAFF 97R obtain this result with a model independent fit to the hadronic structure functions. Fitting with the model of Kuhn and Santamaria (ZPHY **C48**, 445 (1990)) gives 0.87 ± 0.16 ± 0.04, and with the model of of Isgur *et al.* (PR **D39**,1357 (1989)) they obtain 1.20 ± 0.21 ± 0.14.

[209] AKERS 95P obtain this result with a model independent fit to the hadronic structure functions. Fitting with the model of Kuhn and Santamaria (ZPHY **C48**, 445 (1990)) gives $0.87 \pm 0.27^{+0.05}_{-0.06}$, and with the model of of Isgur *et al.* (PR **D39**,1357 (1989)) they obtain $1.10 \pm 0.31^{+0.13}_{-0.14}$.

[210] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result. Replaced by ALBRECHT 95C.

ξ^τ(all hadronic modes) PARAMETER

(V−A) theory predicts $\xi^\tau = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.997±0.009 OUR AVERAGE				
0.93 ±0.10 ±0.04		ABE 97O	SLD	1993–1995 SLC runs
1.29 ±0.26 ±0.11	7.4k	[211] ACKERSTAFF 97R	OPAL	1992–1994 LEP runs
0.995±0.010±0.003	66k	[212] ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
1.03 ±0.06 ±0.04	2.0k	[213] COAN 97	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.970±0.053±0.011	14k	[214] ACCIARRI 96H	L3	1991–1993 LEP runs
1.017±0.039		[215] ALBRECHT 95C	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
1.006±0.032±0.019		[216] BUSKULIC 95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.08\ {}^{+0.46}_{-0.41}\ {}^{+0.14}_{-0.25}$	2.6k	[217] AKERS 95P	OPAL	Repl. by ACKERSTAFF 97R
1.022±0.028±0.030	1.7k	[218] ALBRECHT 94E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.99 ±0.07 ±0.04		[219] BUSKULIC 94D	ALEP	1990+1991 LEP run
$1.25\ \pm0.23\ {}^{+0.15}_{-0.08}$	7.5k	[220] ALBRECHT 93C	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[211] ACKERSTAFF 97R use $\tau \rightarrow a_1 \nu_\tau$ decays.

[212] ALEXANDER 97F use $\tau \rightarrow \rho \nu_\tau$ decays.

[213] COAN 97 use $h^+ h^-$ energy correlations.

[214] ACCIARRI 96H use $\tau \rightarrow \pi \nu_\tau$, $\tau \rightarrow K \nu_\tau$, and $\tau \rightarrow \rho \nu_\tau$ decays.

[215] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.

[216] BUSKULIC 95D use $\tau \rightarrow \pi \nu_\tau$, $\tau \rightarrow \rho \nu_\tau$, and $\tau \rightarrow a_1 \nu_\tau$ decays.

[217] AKERS 95P use $\tau \rightarrow a_1 \nu_\tau$ decays.

[218] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result. Uses $\tau \rightarrow a_1 \nu_\tau$ decays. Replaced by ALBRECHT 95C.

[219] BUSKULIC 94D use $\tau \rightarrow \pi \nu_\tau$ and $\tau \rightarrow \rho \nu_\tau$ decays. Superseded by BUSKULIC 95D.

[220] Uses $\tau \rightarrow a_1 \nu_\tau$ decays. Replaced by ALBRECHT 95C.

τ REFERENCES

ACCIARRI	98C	PL B (to be publ.) CERN-EP/98-15	M. Acciarri+	(L3 Collab.)
ACCIARRI	98E	PL B (to be publ.) CERN-EP/98-45	M. Aciarri+	(L3 Collab.)
ACKERSTAFF	98M	EPJ C (to be publ.) CERN-PPE/97-152	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98N	PL B (to be publ.) CERN-EP/98-033	K. Ackerstaff+	(OPAL Collab.)
BARATE	98	EPJ C1 65	R. Barate+	(ALEPH Collab.)
BARATE	98E	EPJ C (to be publ.) CERN-PPE/97-167	R. Barate+	(ALEPH Collab.)
BLISS	98	PR D57 5903	D.W. Bliss+	(CLEO Collab.)
ABE	97O	PRL 78 4691	+Akagi, Allen, Ash+	(SLD Collab.)
ACKERSTAFF	97J	PL B404 213	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ACKERSTAFF	97L	ZPHY C74 403	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ACKERSTAFF	97R	ZPHY C75 593	K. Ackerstaff+	(OPAL Collab.)
ALEXANDER	97F	PR D56 5320	+Bebek, Berger, Berkelman, Bloom+	(CLEO Collab.)
AMMAR	97B	PRL 78 4686	R. Ammar+	(CLEO Collab.)
ANASTASSOV	97	PR D55 2559	+Blinov, Duboscq, Fisher, Fujino+	(CLEO Collab.)
ANDERSON	97	PRL 79 3814	+Kubota, Lee, O'Neill, Patton+	(CLEO Collab.)
AVERY	97	PR D55 R1119	+Prescott, Yang, Yelton+	(CLEO Collab.)
BARATE	97I	ZPHY C74 387	+Buskulic, Decamp, Ghez, Goy+	(ALEPH Collab.)
BARATE	97R	PL B414 362	R. Barate+	(ALEPH Collab.)
BERGFELD	97	PRL 79 2406	+Eisenstein, Ernst, Gladding+	(CLEO Collab.)
BONVICINI	97	PRL 79 1221	+Cinabro, Green, Perera+	(CLEO Collab.)
BUSKULIC	97C	ZPHY C74 263	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
COAN	97	PR D55 7291	+Fadeyev, Korolkov, Maravin+	(CLEO Collab.)
EDWARDS	97	PR D55 R3919	+Bellerive, Janicek, MacFarlane+	(CLEO Collab.)
EDWARDS	97B	PR D56 R5297	+Bellerive, Janicek, MacFarlane+	(CLEO Collab.)
ESCRIBANO	97	PL B395 369	+Masso	(BARC, PARIT)
ABREU	96B	PL B365 448	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	96H	PL B377 313	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	96K	PL B389 187	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ALAM	96	PRL 76 2637	+Kim, Ling, Mahmood, O'Neill+	(CLEO Collab.)
ALBRECHT	96E	PRPL 276 223	+Andam, Binder, Bockmann+	(ARGUS Collab.)
ALEXANDER	96D	PL B369 163	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96E	PL B374 341	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96S	PL B388 437	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BAI	96	PR D53 20	+Bardon, Becker-Szendy, Blum+	(BES Collab.)
BALEST	96	PL B388 402	+Behrens, Cho, Daoudi, Ford+	(CLEO Collab.)
BARTELT	96	PRL 76 4119	+Csorna, Jain, Marka+	(CLEO Collab.)
BUSKULIC	96	ZPHY C70 579	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	96C	ZPHY C70 561	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
COAN	96	PR D53 6037	+Dominick, Fadeyev, Korolkov+	(CLEO Collab.)
ABE	95Y	PR D52 4828	+Abt, Ahn, Akagi, Allen+	(SLD Collab.)
ABREU	95T	PL B357 715	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	95U	PL B359 411	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	95	PL B345 93	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95F	PL B352 487	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	95F	ZPHY C66 31	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95I	ZPHY C66 543	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95P	ZPHY C67 45	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95Y	ZPHY C68 555	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ALBRECHT	95	PL B341 441	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
ALBRECHT	95C	PL B349 576	+Hamacher, Hofmann, Kirchoff+	(ARGUS Collab.)
ALBRECHT	95G	ZPHY C68 25	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
ALBRECHT	95H	ZPHY C68 215	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
BALEST	95C	PRL 75 3809	+Cho, Ford, Lohner+	(CLEO Collab.)
BUSKULIC	95C	PL B346 371	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	95D	PL B346 379	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
Also	95P	PL B363 265 erratum		
ABREU	94K	PL B334 435	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	94E	PL B328 207	+Alexander, Allison, Anderson+	(OPAL Collab.)
AKERS	94G	PL B339 278	+Alexander, Allison, Anderson+	(OPAL Collab.)
ALBRECHT	94E	PL B337 383	+Hamacher, Hofmann+	(ARGUS Collab.)
ARTUSO	94	PRL 72 3762	+Goldberg, He, Horwitz+	(CLEO Collab.)
BARTELT	94	PRL 73 1890	+Csorna, Egyed, Jain+	(CLEO Collab.)
BATTLE	94	PRL 73 1079	+Ernst, Kwon, Roberts+	(CLEO Collab.)
BAUER	94	PR D50 R13	+Belcinski, Berg, Bingham+	(TPC/2gamma Collab.)
BUSKULIC	94D	PL B321 168	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	94E	PL B332 209	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	94F	PL B332 219	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
GIBAUT	94B	PRL 73 934	+Kinoshita, Barish, Chadha+	(CLEO Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALBRECHT	93C	ZPHY C58 61	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	93G	PL B316 608	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BALEST	93	PR D47 R3671	+Daoudi, Ford, Johnson+	(CLEO Collab.)
BEAN	93	PRL 70 138	+Gronberg, Kutschke+	(CLEO Collab.)
BORTOLETTO	93	PRL 71 1791	+Brown, Fast, McIlwain+	(CLEO Collab.)
ESCRIBANO	93	PL B301 419	+Masso	(BARC)
PROCARIO	93	PRL 70 1207	+Yang, Balest, Cho+	(CLEO Collab.)
ABREU	92N	ZPHY C55 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACTON	92F	PL B281 405	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92H	PL B288 373	+Allison, Allport+	(OPAL Collab.)
AKERIB	92	PRL 69 3610	+Barish, Chadha, Cowen+	(CLEO Collab.)
Also	93B	PRL 71 3395 (erratum)	Akerib, Barish, Chadha, Cowen+	(CLEO Collab.)
ALBRECHT	92D	ZPHY C53 367	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	92K	ZPHY C55 179	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALBRECHT	92M	PL B292 221	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	92Q	ZPHY C56 339	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
AMMAR	92	PR D45 3976	+Baringer, Coppage, Davis+	(CLEO Collab.)
ARTUSO	92	PRL 69 3278	+Goldberg, Horwitz, Kennett+	(CLEO Collab.)
BAI	92	PRL 69 3021	+Bardon, Becker-Szendy, Burnett+	(BES Collab.)
BATTLE	92	PL B291 488	+Ernst, Kroha, Roberts+	(CLEO Collab.)
BUSKULIC	92J	PL B297 459	+Decamp, Goy, Lees+	(ALEPH Collab.)
DECAMP	92C	ZPHY C54 211	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ADEVA	91F	PL B265 451	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ALBRECHT	91D	PL B260 259	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALEXANDER	91D	PL B266 201	+Allison, Allport, Anderson+	(OPAL Collab.)
ANTREASYAN	91	PL B259 216	+Bartels, Besset, Bieler+	(Crystal Ball Collab.)
GRIFOLS	91	PL B255 611	+Mendez	(BARC)
SAMUEL	91B	PRL 67 668	+Li, Mendel	(OKSU, WONT)
Also Erratum.	92B	PRL 69 995	Samuel, Li, Mendel	(OKSU, WONT)
ABACHI	90	PR D41 1414	+Derrick, Kooljman, Musgrave+	(HRS Collab.)
ALBRECHT	90E	PL B246 278	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	90I	PL B250 164	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
BEHREND	90	ZPHY C46 537	+Criegee, Field, Franke+	(CELLO Collab.)
BOWCOCK	90	PR D41 805	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
DELAGUILA	90	PL B252 116	+Sher	(BARC, WILL)
GOLDBERG	90	PL B251 223	+Haupt, Horwitz, Jain+	(CLEO Collab.)
WU	90	PR D41 2339	+Hayes, Perl, Barklow+	(Mark II Collab.)
ABACHI	89B	PR D40 902	+Derrick, Kooljman, Musgrave+	(HRS Collab.)
BEHREND	89B	PL B222 163	+Criegee, Dainton, Field, Franke+	(CELLO Collab.)
JANSSEN	89	PL B228 273	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
KLEINWORT	89	ZPHY C42 7	+Allison, Ambrus, Barlow+	(JADE Collab.)
ADEVA	88	PR D38 2665	+Anderhub, Ansari, Becker+	(Mark-J Collab.)

ALBRECHT	88B	PL B202 149	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88L	ZPHY C41 1	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ALBRECHT	88M	ZPHY C41 405	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
AMIDEI	88	PR D37 1750	+Trilling, Abrams, Baden+	(Mark II Collab.)
BEHREND	88	PL B200 226	+Criegee, Dainton, Field+	(CELLO Collab.)
BRAUNSCH...	88C	ZPHY C39 331	Braunschweig, Kirschfink, Martyn+	(TASSO Collab.)
KEH	88	PL B212 123	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
TSCHIRHART	88	PL B205 407	+Abachi, Akerlof, Baringer+	(HRS Collab.)
ABACHI	87B	PL B197 291	+Baringer, Bylsma, De Bonte+	(HRS Collab.)
ABACHI	87C	PRL 59 2519	+Akerlof, Baringer, Blockus+	(HRS Collab.)
ADLER	87B	PRL 59 1527	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AIHARA	87B	PR D35 1553	+Alston-Garnjost, Avery+	(TPC Collab.)
AIHARA	87C	PRL 59 751	+Alston-Garnjost, Avery+	(TPC Collab.)
ALBRECHT	87L	PL B185 223	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87P	PL B199 580	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
BAND	87	PL B198 297	+Camporesi, Chadwick, Delfino+	(MAC Collab.)
BAND	87B	PRL 59 415	+Bosman, Camporesi, Chadwick+	(MAC Collab.)
BARINGER	87	PRL 59 1993	+Mcllwain, Miller, Shibata+	(CLEO Collab.)
BEBEK	87C	PR D36 690	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BURCHAT	87	PR D35 27	+Feldman, Barklow, Boyarski+	(Mark II Collab.)
BYLSMA	87	PR D35 2269	+Abachi, Baringer, DeBonte+	(HRS Collab.)
COFFMAN	87	PR D36 2185	+Dubois, Eigen, Hauser+	(Mark III Collab.)
DERRICK	87	PL B189 260	+Kooijman, Loos, Musgrave+	(HRS Collab.)
FORD	87	PR D35 408	+Qi, Read, Smith+	(MAC Collab.)
FORD	87B	PR D36 1971	+Qi, Read, Smith+	(MAC Collab.)
GAN	87	PRL 59 411	+Abrams, Amidei, Baden+	(Mark II Collab.)
GAN	87B	PL B197 561	+Abrams, Amidei, Baden+	(Mark II Collab.)
AIHARA	86E	PRL 57 1836	+Alston-Garnjost, Avery+	(TPC Collab.)
BARTEL	86D	PL B182 216	+Becker, Felst, Haidt, Knies+	(JADE Collab.)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
RUCKSTUHL	86	PRL 56 2132	+Stroynowski, Atwood, Barish+	(DELCO Collab.)
SCHMIDKE	86	PRL 57 527	+Abrams, Matteuzzi, Amidei+	(Mark II Collab.)
YELTON	86	PRL 56 812	+Dorfan, Abrams, Amidei+	(Mark II Collab.)
ALTHOFF	85	ZPHY C26 521	+Braunschweig, Kirschfink+	(TASSO Collab.)
ASH	85B	PRL 55 2118	+Band, Blume, Camporesi+	(MAC Collab.)
BALTRUSAIT...	85	PRL 55 1842	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BARTEL	85F	PL 161B 188	+Becker, Cords, Felst+	(JADE Collab.)
BEHRENDS	85	PR D32 2468	+Gentile, Guida, Guida, Morrow+	(CLEO Collab.)
BELTRAMI	85	PRL 54 1775	+Bylsma, DeBonte, Gan+	(HRS Collab.)
BERGER	85	ZPHY C28 1	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BURCHAT	85	PRL 54 2489	+Schmidke, Yelton, Abrams+	(Mark II Collab.)
FERNANDEZ	85	PRL 54 1624	+Ford, Qi, Read+	(MAC Collab.)
MILLS	85	PRL 54 624	+Pal, Atwood, Baillon+	(DELCO Collab.)
AIHARA	84C	PR D30 2436	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
BEHREND	84	ZPHY C23 103	+Fenner, Schachter, Schroder+	(CELLO Collab.)
MILLS	84	PRL 52 1944	+Ruckstuhl, Atwood, Baillon+	(DELCO Collab.)
BEHREND	83C	PL 127B 270	+Chen, Fenner, Gumpel+	(CELLO Collab.)
SILVERMAN	83	PR D27 1196	+Shaw	(UCI)
BEHREND	82	PL 114B 282	+Chen, Fenner, Field+	(CELLO Collab.)
BLOCKER	82B	PRL 48 1586	+Abrams, Alam, Blondel+	(Mark II Collab.)
BLOCKER	82D	PL 109B 119	+Dorfan, Abrams, Alam+	(Mark II Collab.) J
FELDMAN	82	PRL 48 66	+Trilling, Abrams, Amidei+	(Mark II Collab.)
HAYES	82	PR D25 2869	+Perl, Alam, Boyarski+	(Mark II Collab.)
BERGER	81B	PL 99B 489	+Genzel, Grigull, Lackas+	(PLUTO Collab.)
DORFAN	81	PRL 46 215	+Blocker, Abrams, Alam+	(Mark II Collab.)
BRANDELIK	80	PL 92B 199	+Braunschweig, Gather+	(TASSO Collab.)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)
BACINO	79B	PRL 42 749	+Ferguson, Nodulman, Slater+	(DELCO Collab.)
KIRKBY	79	SLAC-PUB-2419 Batavia Lepton Photon Conference.		(SLAC) J
BACINO	78B	PRL 41 13	+Ferguson, Nodulman, Slater+	(DELCO Collab.) J
Also	78	Tokyo Conf. 249	Kirz	(STON)
Also	80	PL 96B 214	Zholentz, Kurdadze, Lelchuk, Mishnev+	(NOVO)
BRANDELIK	78	PL 73B 109	+Braunschweig, Martyn, Sander+	(DASP Collab.) J
FELDMAN	78	Tokyo Conf. 777		(SLAC) J
HEILE	78	NP B138 189	+Perl, Abrams, Alam, Boyarski+	(SLAC, LBL)
JAROS	78	PRL 40 1120	+Abrams, Alam+	(SLAC, LBL, NWES, HAWA)
PERL	75	PRL 35 1489	+Abrams, Boyarski, Breidenbach+	(LBL, SLAC)

OTHER RELATED PAPERS

GENTILE	96	PRPL 274 287	+Pohl	(ROMAI, ETH)
WEINSTEIN	93	ARNPS 43 457	+Stroynowski	(CIT, SMU)
PERL	92	RPP 55 653		(SLAC)
PICH	90	MPL A5 1995		(VALE)
BARISH	88	PRPL 157 1	+Stroynowski	(CIT)
GAN	88	IJMP A3 531	+Perl	(SLAC)
HAYES	88	PR D38 3351	+Perl	(SLAC)
PERL	80	ARNPS 30 299		(SLAC)

Heavy Charged Lepton Searches

Charged Heavy Lepton MASS LIMITS

Sequential Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

These experiments assumed that a fourth generation $L^{\pm}$ decayed to a fourth generation ν_L (or L^0) where ν_L was stable, or that $L^{\pm}$ decays to a light ν_ℓ via mixing.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited leptons, *i.e.* $\ell^* \to \ell\gamma$. See the "WIMPs and other Particle Searches" section for heavy charged particle search limits in which the charged particle could be a lepton.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>81.5	95	ACKERSTAFF	98C	OPAL	Assumed $m_{L^{\pm}} - m_{L^0} > 8.4$ GeV
>80.2	95	ACKERSTAFF	98C	OPAL	$m_{L^0} > m_{L^{\pm}}$ and $L^{\pm} \to \nu W$
>72	95	ACCIARRI	97P	L3	Assumed $m_{L^{\pm}} - m_{\nu_L} > 10$ GeV
>81	95	ACCIARRI	97P	L3	Assumed $m_{L^{\pm}} - m_{\nu_L} > 20$ GeV
>78.7	95	ACCIARRI	97P	L3	Light ν, $\sqrt{s}$=161, 172 GeV
< 48 or > 61	95	[1] ACCIARRI	96G	L3	
>64.5	95	ALEXANDER	96P	OPAL	$m_L - m_{L^0} > 10$ GeV
>63.5	95	BUSKULIC	96S	ALEP	$m_L - m_{L^0} > 7$ GeV
>42.8	95	ADEVA	90S	L3	Decay to Dirac ν_L
>44.3	95	AKRAWY	90G	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>73.5	95	ACKERSTAFF	97D	OPAL	Assumed $m_{L^{\pm}} - m_{\nu_L} > 13$ GeV
>76.7	95	ACKERSTAFF	97D	OPAL	$m_{\nu_L} > m_{L^{\pm}}$ and $L^{\pm} \to \nu W^*$
>63.9	95	ALEXANDER	96P	OPAL	Decay to massless ν's
>65	95	BUSKULIC	96S	ALEP	Decay to massless ν's
none 10–225		[2] AHMED	94	CNTR	H1 Collab. at HERA
none 12.6–29.6	95	KIM	91B	AMY	Massless ν assumed
>42.7	95	DECAMP	90F	ALEP	
none 0.5–10	95	[3] RILES	90	MRK2	For (m_{L^0}-m_{L^0})> 0.25–0.4GeV
> 8		[4] STOKER	89	MRK2	For ($m_{L^+} - m_{L^0}$)= 0.4 GeV
>12		[4] STOKER	89	MRK2	For m_{L^0}=0.9 GeV
none 18.4–27.6	95	[5] ABE	88	VNS	
>25.5	95	[6] ADACHI	88B	TOPZ	
none 1.5–22.0	95	BEHREND	88C	CELL	
>41	90	[7] ALBAJAR	87B	UA1	
>22.5	95	[8] ADEVA	85	MRKJ	
>18.0	95	[9] BARTEL	83	JADE	
none 4–14.5	95	[10] BERGER	81B	PLUT	
>15.5	95	[11] BRANDELIK	81	TASS	
>13.		[12] AZIMOV	80		
>16.	95	[13] BARBER	80B	CNTR	
> 0.490		[14] ROTHE	69	RVUE	

[1] ACCIARRI 96G assumes LEP result that the associated neutral heavy lepton mass > 40 GeV.

[2] The AHMED 94 limits are from a search for neutral and charged sequential heavy leptons at HERA via the decay channels $L^- \to e\gamma$, $L^- \to \nu W^-$, $L^- \to eZ$; and $L^0 \to \nu\gamma$, $L^0 \to e^- W^+$, $L^- \to \nu Z$, where the W decays to $\ell\nu_\ell$, or to jets, and Z decays to $\ell^+\ell^-$ or jets.

[3] RILES 90 limits were the result of a special analysis of the data in the case where the mass difference $m_{L^-} - m_{L^0}$ was allowed to be quite small, where L^0 denotes the neutrino into which the sequential charged lepton decays. With a slightly reduced $m_{L^{\pm}}$ range, the mass difference extends to about 4 GeV.

[4] STOKER 89 (Mark II at PEP) gives bounds on charged heavy lepton (L^+) mass for the generalized case in which the corresponding neutral heavy lepton (L^0) in the SU(2) doublet is not of negligible mass.

[5] ABE 88 search for L^+ and $L^- \to$ hadrons looking for acoplanar jets. The bound is valid for $m_\nu < 10$ GeV.

[6] ADACHI 88B search for hadronic decays giving acoplanar events with large missing energy. $E_{cm}{}^{ee} = 52$ GeV.

[7] Assumes associated neutrino is approximately massless.

[8] ADEVA 85 analyze one-isolated-muon data and sensitive to τ <10 nanosec. Assume B(lepton) = 0.30. E_{cm} = 40–47 GeV.

[9] BARTEL 83 limit is from PETRA e^+e^- experiment with average E_{cm} = 34.2 GeV.

[10] BERGER 81B is DESY DORIS and PETRA experiment. Looking for $e^+e^- \to L^+L^-$.

[11] BRANDELIK 81 is DESY-PETRA experiment. Looking for $e^+e^- \to L^+L^-$.

[12] AZIMOV 80 estimated probabilities for $M + N$ type events in $e^+e^- \to L^+L^-$ deducing semi-hadronic decay multiplicities of L from e^+e^- annihilation data at $E_{cm} = (2/3)m_L$. Obtained above limit comparing these with e^+e^- data (BRANDELIK 80).

[13] BARBER 80B looked for $e^+e^- \to L^+L^-$, $L \to \nu_L^+ X$ with MARK-J at DESY-PETRA.

[14] ROTHE 69 examines previous data on μ pair production and π and K decays.

Stable Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*
>84.2	95	ACCIARRI	97P	L3
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>28.2	95	[15] ADACHI	90C	TOPZ
none 18.5–42.8	95	AKRAWY	90O	OPAL
>26.5	95	DECAMP	90F	ALEP
none m_μ–36.3	95	SODERSTROM	90	MRK2

[15] ADACHI 90C put lower limits on the mass of stable charged particles with electric charge Q satisying $2/3 < Q/e < 4/3$ and with spin 0 or 1/2. We list here the special case for a stable charged heavy lepton.

Charged Long-Lived Heavy Lepton MASS LIMITS

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.1	0	[16] ANSORGE	73B	HBC	−	Long-lived
none 0.55–4.5		[17] BUSHNIN	73	CNTR	−	Long-lived
none 0.2–0.92		[18] BARNA	68	CNTR	−	Long-lived
none 0.97–1.03		[18] BARNA	68	CNTR	−	Long-lived

[16] ANSORGE 73B looks for electron pair production and electron-like Bremsstrahlung.

[17] BUSHNIN 73 is SERPUKOV 70 GeV p experiment. Masses assume mean life above 7×10^{-10} and 3×10^{-8} respectively. Calculated from cross section (see "Charged Quasi-Stable Lepton Production Differential Cross Section" below) and 30 GeV muon pair production data.

[18] BARNA 68 is SLAC photoproduction experiment.

Doubly-Charged Heavy Lepton MASS LIMITS

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–9 GeV	90	[19] CLARK	81	SPEC	++

[19] CLARK 81 is FNAL experiment with 209 GeV muons. Bounds apply to μ_p which couples with full weak strength to muon. See also section on "Doubly-Charged Lepton Produciton Cross Section."

Doubly-Charged Lepton Production Cross Section (μN Scattering)

VALUE (cm^2)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.\times10^{-38}$	0	[20] CLARK	81	SPEC	++

[20] CLARK 81 is FNAL experiment with 209 GeV muon. Looked for μ^+ nucleon $\rightarrow$ $\vec{\mu}_P^0$X, $\vec{\mu}_P^0 \rightarrow \mu^+\mu^-\overline{\nu}_\mu$ and $\mu^+ n \rightarrow \mu_P^{++}$X, $\mu_P^{++} \rightarrow 2\mu^+\nu_\mu$. Above limits are for $\sigma\times$BR taken from their mass-dependence plot figure 2.

REFERENCES FOR Heavy Charged Lepton Searches

ACKERSTAFF	98C	EPJ C1 45	K. Ackerstaff+	(OPAL Collab.)
ACCIARRI	97P	PL B412 189	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACKERSTAFF	97D	PL B393 217	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ACCIARRI	96G	PL B377 304	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ALEXANDER	96P	PL B385 433	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96S	PL B384 439	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
AHMED	94	PL B340 205	+	(H1 Collab.)
KIM	91B	IJMP A6 2583	+Smith, Breedon, Ko+	(AMY Collab.)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
ADEVA	90S	PL B251 321	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
AKRAWY	90G	PL B240 250	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90O	PL B252 290	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90F	PL B236 511	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
RILES	90	PR D42 1	+Perl, Barklow+	(Mark II Collab.)
SODERSTROM	90	PRL 64 2980	+McKenna, Abrams, Adolphsen, Averill+	(Mark II Collab.)
STOKER	89	PR D39 1811	+Perl, Abrams+	(Mark II Collab.)
ABE	88	PRL 61 915	+Amako, Arai, Asano, Chiba	(VENUS Collab.)
ADACHI	88B	PR D37 1339	+Aihara, Dijkstra, Enomoto+	(TOPAZ Collab.)
BEHREND	88C	ZPHY C41 7	+Buerger, Criegee, Dainton+	(CELLO Collab.)
ALBAJAR	87B	PL B185 241	+Albrow, Allkofer, Arnison+	(UA1 Collab.)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
Also	84C	PRPL 109 131	Adeva, Barber, Becker+	(Mark-J Collab.)
BARTEL	83	PL 123B 353	+Cords, Dietrich, Eichler+	(JADE Collab.)
BERGER	81B	PL 99B 489	+Genzel, Grigull, Lackas+	(PLUTO Collab.)
BRANDELIK	81	PL 99B 163	+Braunschweig, Gather+	(TASSO Collab.)
CLARK	81	PRL 46 299	+Johnson, Kerth, Loken+	(UCB, LBL, FNAL, PRIN)
Also	82	PR D25 2762	Smith, Clark, Johnson, Kerth+	(LBL, FNAL, PRIN)
AZIMOV	80	JETPL 32 664	+Khoze	(PNPI)
		Translated from ZETFP 32 677.		
BARBER	80B	PRL 45 1904	+Becker, Bei, Berghoff+	(Mark-J Collab.)
BRANDELIK	80	PL 92B 199	+Braunschweig, Gather+	(TASSO Collab.)
ANSORGE	73B	PR D7 26	+Baker, Krzesinski, Neale, Rushbrooke+	(CAVE)
BUSHNIN	73	NP B58 476	+Dunaitzev, Golovkin, Kubarovsky+	(SERP)
Also	72	PL 42B 136	Golovkin, Grachev, Shodyrev+	(SERP)
ROTHE	69	NP B10 241	+Wolsky	(PENN)
BARNA	68	PR 173 1391	+Cox, Martin, Perl, Tan, Toner, Zipf+	(SLAC, STAN)

OTHER RELATED PAPERS

PERL	81	SLAC-PUB-2752		(SLAC)
		Physics in Collision Conference.		

NEUTRINO MASS

Written February 1998 by B. Kayser (NSF).

While there is no unequivocal evidence for neutrino mass, it is natural to suspect that the neutrinos, like the charged leptons and the quarks, have nonzero masses. Evidence of these masses is being sought through experiments on neutrinos created astrophysically, in the earth's atmosphere, by accelerators, by reactors, and by nuclear decays, and in studies of reactions where neutrinos appear only as virtual particles.

In the decay

$$W^+ \rightarrow \ell^+\nu_\ell \tag{1}$$

of a W boson into a charged lepton of "flavor" $\ell(e, \mu$, or $\tau)$, the accompanying neutrino is referred to as ν_ℓ, the neutrino of flavor ℓ. Neutrinos of different flavor are different objects. When an energetic ν_ℓ undergoes a charged-current weak interaction, it produces a charged lepton ℓ of the same flavor as the neutrino [1].

If neutrinos have masses, then a neutrino of definite flavor, ν_ℓ, need not be a mass eigenstate. Indeed, if leptons behave like quarks, the ν_ℓ is a coherent linear superposition of mass eigenstates, given by

$$|\nu_\ell\rangle = \sum_m U_{\ell m}|\nu_m\rangle \ . \tag{2}$$

Here, the ν_m are the mass eigenstates, and the coefficients $U_{\ell m}$ form a matrix U known as the leptonic mixing matrix. There are at least three ν_m, and perhaps more. However, it is usually assumed that no more than three ν_m make significant contributions to Eq. (2). Then U is a 3×3 matrix, and according to the electroweak Standard Model (SM), extended to include neutrino masses, it is unitary.

The relation (2) means that when, for example, a W^+ decays to an e^+ and a neutrino, the neutrino with probability $|U_{e1}|^2$ is a ν_1, with probability $|U_{e2}|^2$ is a ν_2, and so on. This behavior is an exact leptonic analogue of what is known to occur when a W^+ decays to quarks.

If each neutrino of definite flavor is a coherent superposition of mass eigenstates, then we will have *neutrino oscillation* [2]. This is the spontaneous metamorphosis of a neutrino of one flavor into one of another flavor as the neutrino propagates.

To understand neutrino oscillation, let us consider how a neutrino born as the ν_ℓ of Eq. (2) evolves in time. First, we apply Schrödinger's equation to the ν_m component of ν_ℓ in the rest frame of that component. This tells us that [3]

$$|\nu_m(\tau_m)\rangle = e^{-iM_m\tau_m}|\nu_m(0)\rangle \ , \tag{3}$$

where M_m is the mass of ν_m, and τ_m is time in the ν_m frame. In terms of the time t and position L in the laboratory frame, the Lorentz-invariant phase factor in Eq. (3) may be written

$$e^{-iM_m\tau_m} = e^{-i(E_mt-p_mL)} \ . \tag{4}$$

Here, E_m and p_m are respectively the energy and momentum of ν_m in the laboratory frame. In practice, our neutrino will be extremely relativistic, so we will be interested in evaluating the phase factor of Eq. (4) where $t \approx L$, where it becomes $\exp[-i(E_m - p_m)L]$.

Imagine now that our ν_ℓ has been produced with a definite momentum p, so that all of its mass-eigenstate components have this common momentum. Then the ν_m component has $E_m = \sqrt{p^2 + M_m^2} \approx p + M_m^2/2p$, assuming that all neutrino masses M_m are small compared to the neutrino momentum. The phase factor of Eq. (4) is then approximately

$$e^{-i(M_m^2/2p)L} \ . \tag{5}$$

Alternatively, suppose that our ν_ℓ has been produced with a definite energy E, so that all of its mass-eigenstate components have this common energy [4]. Then the ν_m component has $p_m = \sqrt{E^2 - M_m^2} \approx E - M_m^2/2E$. The phase factor of Eq. (4) is then approximately

$$e^{-i(M_m^2/2E)L} \ . \tag{6}$$

Since highly relativistic neutrinos have $E \approx p$, the phase factors (5) and (6) are approximately equal. Thus, it doesn't matter whether our ν_ℓ is created with definite momentum or definite energy.

From Eq. (2) and either Eq. (5) or Eq. (6), it follows that after a neutrino born as a ν_ℓ has propagated a distance L, its state vector has become

$$|\nu_\ell(L)\rangle \approx \sum_m U_{\ell m} e^{-i(M_m^2/2E)L}|\nu_m\rangle \ . \tag{7}$$

Using the unitarity of U to invert Eq. (2), and inserting the result in Eq. (7), we find that

$$|\nu_\ell(L)\rangle \approx \sum_{\ell'} \left[\sum_m U_{\ell m} e^{-i(M_m^2/2E)L} U^*_{\ell' m} \right] |\nu_{\ell'}\rangle \ . \qquad (8)$$

We see that our ν_ℓ, in traveling the distance L, has turned into a superposition of all the flavors. The probability that it has flavor ℓ', $P(\nu_\ell \to \nu_{\ell'}; L)$, is obviously given by

$$P(\nu_\ell \to \nu_{\ell'};\ L) = |\langle \nu_{\ell'}|\nu_\ell(L)\rangle|^2 = \left| \sum_m U_{\ell m} e^{-i(M_m^2/2E)L} U^*_{\ell' m} \right|^2 \ . \qquad (9)$$

The quantum mechanics of neutrino oscillation leading to the result Eq. (9) is somewhat subtle. It has been analyzed using wave packets [5], treating a propagating neutrino as a virtual particle [6], evaluating the phase acquired by a propagating mass eigenstate in terms of the proper time of propagation [3], requiring that a neutrino's flavor cannot change unless the neutrino travels [4], and taking different neutrino mass eigenstates to have both different momenta and different energies [7]. The subtleties of oscillation are still being explored and discussed.

Frequently, a neutrino oscillation experiment is analyzed assuming that only two neutrino flavors, ν_e and ν_μ for example, mix appreciably. Then the mixing matrix U takes the form

$$U = \begin{pmatrix} \cos\theta_{e\mu} & \sin\theta_{e\mu} \\ -\sin\theta_{e\mu} & \cos\theta_{e\mu} \end{pmatrix} \ , \qquad (10)$$

where $\theta_{e\mu}$ is the ν_e–ν_μ mixing angle. Inserting this matrix into Eq. (9), we find that

$$P(\nu_e \to \nu_\mu;\ L) = \sin^2 2\theta_{e\mu} \sin^2\left(\Delta M^2_{12} L/4E\right) \ . \qquad (11)$$

Here, $\Delta M^2_{12} \equiv M_1^2 - M_2^2$, where ν_1 and ν_2 are the mass eigenstates which make up ν_e and ν_μ. If the omitted factors of $\hbar$ and c are inserted into the argument $\Delta M^2_{12} L/4E$ of the oscillatory sine function, it becomes 1.27 ΔM^2_{12} (eV^2)L (km)/E (GeV). The probability that a ν_e will retain its original flavor during propagation over a distance L is simply

$$P(\nu_e \to \nu_e;\ L) = 1 - P(\nu_e \to \nu_\mu;\ L) \ . \qquad (12)$$

Under some important circumstances, a "two-neutrino" formula virtually identical to that of Eq. (11) accurately describes neutrino oscillation even when all three neutrino flavors mix. One of these circumstances is when all mixing angles are small. That is, each neutrino of definite flavor is dominantly one mass eigenstate, plus only small amounts of the other two. In this circumstance, let us refer to the dominant mass eigenstate component of ν_e as ν_1, that of ν_μ as ν_2, and that of ν_τ as ν_3. Then the mixing matrix U is approximately

$$U \approx \begin{pmatrix} 1 & \theta_{e\mu} & \theta_{e\tau} \\ -\theta_{e\mu} & 1 & \theta_{\mu\tau} \\ -\theta_{e\tau} & -\theta_{\mu\tau} & 1 \end{pmatrix} \ , \qquad (13)$$

where θ_{ab} is the (small) ν_{ℓ_a}–ν_{ℓ_b} mixing angle. Inserting this mixing matrix in Eq. (9), we find that through second order in the mixing angles,

$$P(\nu_{\ell_a} \to \nu_{\ell_b \neq \ell_a};\ L) \approx (2\theta_{ab})^2 \sin^2\left(\Delta M^2_{ij} L/4E\right) \ . \qquad (14)$$

Here, $\Delta M^2_{ij} \equiv M_i^2 - M_j^2$, where ν_i and ν_j are, respectively, the dominant mass eigenstate components of ν_{ℓ_a} and ν_{ℓ_b}. We see that when all mixing angles are small, the oscillation between any pair of neutrino flavors is indeed described by a two-neutrino formula just like Eq. (11), but for each pair of flavors, there is a different mixing angle and a different ΔM^2. In addition, in contrast to Eq. (12), the probability that a neutrino (say, a ν_e) retains its original flavor is now given by

$$P(\nu_e \to \nu_e;\ L) = 1 - P(\nu_e \to \nu_\mu;\ L) - P(\nu_e \to \nu_\tau;\ L) \ . \ (15)$$

Another interesting situation occurs when there is a neutrino mass hierarchy, $M_3 \gg M_2 \gg M_1$, so that $\Delta M^2_{32} \approx \Delta M^2_{31} \gg \Delta M^2_{21}$. Then there is a region of L/E in which $\Delta M^2_{21} L/E$ is negligible compared to unity, but $\Delta M^2_{32}\ L/E$ is not. For L/E in this region, it follows from Eq. (9) and the unitarity of U that [8]

$$P(\nu_{\ell_a} \to \nu_{\ell_b \neq \ell_a};\ L) \approx |2U_{a3}U_{b3}|^2 \sin^2\left(\Delta M^2_{32} L/4E\right) \ . \qquad (16)$$

Once again, the oscillation probability has the same form as when just two neutrinos mix. Furthermore, Eq. (16) holds whether the mixing angles are large or small. However, the parameters in Eq. (16) have a different meaning from those in the true two-neutrino formula, Eq. (11). In Eq. (16), the coefficient $|2U_{a3}U_{b3}|^2$ is, in general, *not* $\sin^2 2\theta_{ab}$, as it would be in the two-neutrino case. (To be sure, $|2U_{a3}U_{b3}|^2$ never exceeds unity, anymore than $\sin^2 2\theta_{ab}$ does.) In addition, in Eq. (16), the mass splitting which appears is always the same one—ΔM^2_{32}—regardless of which neutrino flavors are being considered.

In a beam of neutrinos born with flavor ℓ_a, neutrino oscillation can be sought in two ways: First, one may seek the *appearance* in the beam of neutrinos of a different flavor, ℓ_b. Secondly, one may seek a *disappearance* of some of the original ν_{ℓ_a} flux, or an L-dependence of this flux.

Clearly, no oscillation is expected unless L/E of the experiment is sufficiently large that the phase factors $\exp(-iM^2_m\ L/2E)$ in Eq. (9) differ appreciably from one another. Otherwise, $\mathrm{P}(\nu_\ell \to \nu_{\ell'}; L) = |\sum_m U_{\ell m} U^*_{\ell' m}|^2 = \delta_{\ell\ell'}$. Now, with omitted factors of $\hbar$ and c inserted, the relative phase of $\exp(-iM_i^2 L/2E)$ and $\exp(-iM_j^2 L/2E)$ is 2.54 ΔM^2_{ij}(eV^2) L(km)/E(GeV). Thus, for example, an experiment in which neutrinos with $E \approx 1$ GeV travel 1 km between production and detection will be sensitive to $\Delta M^2 \gtrsim 1$ eV^2.

A more direct way than neutrino oscillation experiments to search for neutrino mass is to look for its kinematical effects in decays which produce a neutrino. In the decay $X \to Y\ell^+\nu_\ell$, where X is a hadron and Y is zero or more hadrons, the momenta of ℓ^+ and the particles in Y will obviously be modified if ν_ℓ has a mass. If ν_ℓ is a superposition of mass eigenstates ν_m, then $X \to Y\ell^+\nu_\ell$ is actually the sum of the decays $X \to Y\ell^+\nu_m$ yielding every ν_m light enough to be emitted. Thus, if, for example, one ν_m is much heavier than the others, the energy spectrum of ℓ^+ may show a threshold rise where the ℓ^+ energy becomes low enough for the heavy ν_m to be emitted [9]. However, if neutrino mixing is small, then the decays $X \to Y\ell^+\nu_m$ yield almost always the neutrino mass eigenstate which is the dominant component of ν_ℓ. The kinematics of ℓ^+ and Y then reflect the mass of this mass eigenstate.

From kinematical studies of the particles produced in ${}^3\mathrm{H} \to {}^3\mathrm{He}\ e^-\overline{\nu}_e, \pi \to \mu\nu_\mu$, and $\tau \to n\pi\nu_\tau$, upper limits have been derived for M_1, M_2, and M_3, respectively. Here, we assume mixing to be small, and, as before, call the dominant mass-eigenstate components of ν_e, ν_μ, and ν_τ, respectively, ν_1, ν_2, and ν_3. In the case of the decay ${}^3\mathrm{H} \to {}^3\mathrm{He}\ e^-\overline{\nu}_e$, the upper bound on the neutrino mass is derived from study of the e^- energy spectrum. It should be noted that in several experiments, the theoretical expression used to describe this spectrum does not produce a good fit, either for $M_1 = 0$ or for $M_1 > 0$ [10]. Indeed, the best fit is achieved for an unphysical, *negative* value of M_1^2. Thus, the quoted limits on M_1 must be interpreted with caution.

Neutrinos carry neither electric charge nor, as far as we know, any other charge-like quantum numbers. To be sure, it may be that the reason an interacting "neutrino" creates an ℓ^-, while an "antineutrino" creates an ℓ^+, is that neutrinos and antineutrinos carry opposite values of a conserved "lepton number." However, there may be no lepton number. Even then, the fact that "neutrinos" and "antineutrinos" interact differently can be easily understood. One need only note that, in practice, the particles we call "neutrinos" are always left-handed, while the ones we call "antineutrinos" are right-handed. Since the weak interactions are not invariant under parity, it is then possible to attribute the difference between the interactions of "neutrinos" and "antineutrinos" to the fact that these particles are oppositely polarized.

If the neutrino mass eigenstates do not carry any charge-like attributes, they may be their own antiparticles. A neutrino which is its own antiparticle is called a Majorana neutrino, while one which is not is called a Dirac neutrino.

If neutrinos are of Majorana character, we can have neutrinoless double beta-decay ($\beta\beta_{0\nu}$), in which one nucleus decays to another by emitting two electrons and nothing else. This process can be initiated through the emission of two virtual W bosons by the parent nucleus. One of these W bosons then emits an electron and an accompanying virtual "antineutrino." In the Majorana case, this "antineutrino" is no different from a "neutrino," except for its right-handed helicity. If the virtual neutrino has a mass, then (like the e^+ in nuclear β-decay), it is not fully right-handed, but has a small amplitude, proportional to its mass, for being left-handed. Its left-handed component is precisely what we call a "neutrino," and can be absorbed by the second virtual W boson to create the second outgoing electron. This mechanism yields for $\beta\beta_{0\nu}$ an amplitude proportional to an effective neutrino mass $\langle M\rangle$, given in a common phase convention by [11]

$$\langle M\rangle = \sum_m U_{em}^2 M_m \ . \tag{17}$$

Experimental upper bounds on the $\beta\beta_{0\nu}$ rate are used to derive upper bounds on $\langle M\rangle$. Note that, owing to possible phases in the mixing matrix elements U_{em}, the relation between $\langle M\rangle$ and the actual masses M_m of the neutrino mass eigenstates can be somewhat complicated. The process $\beta\beta_{0\nu}$ is discussed further by P. Vogel in this *Review*.

If neutrinos are their own antiparticles, then their magnetic and electric dipole moments must vanish. To see why, recall that CPT invariance requires that the dipole moments of the electron and its antiparticle be equal and opposite. Similarly, CPT invariance would require that the dipole moments of a neutrino and its antiparticle be equal and opposite. But, if the antiparticle of the neutrino is the neutrino itself, this means that the dipole moments must vanish [12].

If neutrinos are not their own antiparticles, then they can have dipole moments. However, for a Dirac neutrino mass eigenstate ν_m, the magnetic dipole moment μ_m predicted by the Standard Model (extended to include neutrino masses) is only [13]

$$\mu_m = 3.2 \times 10^{-19} M_m(\mathrm{eV})\mu_B \ , \tag{18}$$

where μ_B is the Bohr magneton.

Whether neutrinos are their own antiparticles or not, there may be *transition* magnetic and electric dipole moments. These induce the transitions $\nu_m \to \nu_{m'\neq m}\gamma$.

A Majorana neutrino, being its own antiparticle, obviously consists of just two states: spin up and spin down. In contrast, a Dirac neutrino, together with its antiparticle, consists of four states: the spin-up and spin-down neutrino states, plus the spin-up and spin-down antineutrino states. A four-state Dirac neutrino may be pictured as comprised of two degenerate two-state Majorana neutrinos. Conversely, in the field-theory description of neutrinos, by introducing so-called Majorana mass terms, one can split a Dirac neutrino, D, into two nondegenerate Majorana neutrinos, ν and N. In some extensions of the SM, it is natural for the D, ν, and N masses, M_D, M_ν, and M_N, to be related by

$$M_\nu M_N \approx M_D^2 \ . \tag{19}$$

In these extensions, it is also natural for M_D to be of the order of $M_{\ell \text{ or } q}$, the mass of a typical charged lepton or quark. Then we have [14]

$$M_\nu M_N \sim M_{\ell \text{ or } q}^2 \ . \tag{20}$$

Suppose now that $M_N \gg M_{\ell \text{ or } q}$, so that N is a very heavy neutrino which has not yet been observed. Then relation (20), known as the seesaw relation, implies that $M_\nu \ll M_{\ell \text{ or } q}$. Thus, ν is a candidate for one of the light neutrino mass eigenstates which make up ν_e, ν_μ, and ν_τ. So long as N is heavy, the seesaw relation explains, without fine tuning, why a mass eigenstate component of ν_e, ν_μ, or ν_τ will be light. Interestingly, the picture from which the seesaw relation arises predicts that the mass eigenstate components of ν_e, ν_μ, and ν_τ are Majorana neutrinos.

In early 1998, there are three observed hints of neutrino oscillation, and thus of neutrino mass. These hints are the behavior of solar neutrinos, the behavior of atmospheric neutrinos, and the results of the LSND experiment.

The flux of solar neutrinos has been detected on earth by several experiments [15] with different neutrino energy thresholds. In every experiment, the flux is found to be below the corresponding prediction of the Standard Solar Model (SSM) [16]. The discrepancies between the observed fluxes and the SSM predictions have proven very difficult to explain by simply modifying the SSM, without invoking neutrino mass [17]. Indeed, we know of no attempt which has succeeded. By contrast, all the existing observations can successfully and elegantly be explained if one does invoke neutrino mass. The most popular explanation of this type is based on the Mikheyev-Smirnov-Wolfenstein (MSW) effect—a matter-enhanced neutrino oscillation [18].

The neutrinos produced by the nuclear processes that power the sun are electron neutrinos ν_e. With some probability, the MSW effect converts a ν_e into a neutrino ν_x of another flavor. Depending on the specific version of the effect, ν_x is a ν_μ, a ν_τ, a ν_μ-ν_τ mixture, or perhaps a sterile neutrino ν_s. Since present solar neutrino detectors are sensitive to a ν_e, but wholly, or at least largely, insensitive to a ν_μ, ν_τ, or ν_s, the flavor conversion accounts for the low observed fluxes.

The MSW $\nu_e \to \nu_x$ conversion results from interaction between neutrinos and solar electrons as the neutrinos travel outward from the solar core, where they were produced. The conversion requires that, somewhere in the sun, the total energy of a ν_e of given momentum, including the energy of its interaction with the solar electrons, equal the total energy of the ν_x of the same momentum, so that we have an energy level crossing. Given the typical density of solar electrons, and the typical momenta of solar neutrinos, the condition that there be a level crossing requires that

$$M^2_{\nu_x} - M^2_{\nu_e} \equiv \Delta M^2_{\nu_x \nu_e} \sim 10^{-5}\text{eV}^2 \;, \tag{21}$$

where M_{ν_e} is the mass of the dominant mass eigenstate component of ν_e, and M_{ν_x} is the mass of ν_x.

The solar neutrino observations can also be explained by supposing that on their way from the sun to the earth, the electron neutrinos produced in the solar core undergo vacuum oscillation into neutrinos of another flavor [19]. Assuming that only two neutrino flavors are important to this oscillation, the oscillation probability is described by an expression of the form given by Eq. (11). To explain the observed suppression of the solar ν_e flux to less than half the predicted value at some energies, and to accommodate the observation that the suppression is energy-dependent, the argument $[1.27\Delta M^2(\text{eV}^2)L(\text{km})/E(\text{GeV})]$ of the oscillatory factor in Eq. (11) must be of order unity when L is the distance from the sun to the earth, and $E \simeq 1$ MeV is the typical energy of a solar neutrino. Perhaps this apparent coincidence makes the vacuum oscillation explanation of the solar neutrino observations less likely than the MSW explanation. To have $[1.27\Delta M^2(\text{eV}^2)L(\text{km})/E(\text{GeV})]{\sim}\ 1$, we require that $\Delta M^2 \sim 10^{-10}$ eV^2.

The solar neutrino experiments, and the comparison between their results and theoretical predictions, are discussed in some detail by K. Nakamura in this *Review*.

Neutrinos created in the earth's atmosphere by cosmic rays result largely from the cosmic-ray-induced production of pions, which then decay via the chain $\pi \to \mu\nu_\mu$, $\mu \to e\nu_e\nu_\mu$. As we see, this chain produces neutrinos in the ratio $\nu_\mu : \nu_e = 2:1$. Since the various neutrinos from the chain have different energy spectra, this 2:1 ratio does not hold at a given neutrino energy, but it is believed that the actual $\nu_\mu : \nu_e$ ratio is known to 5% [20]. However, measurements of this ratio in underground detectors yield [21]

$$R \equiv \frac{(\nu_\mu\!:\!\nu_e)_{\text{Data}}}{(\nu_\mu\!:\!\nu_e)_{\text{MC}}} \approx 0.6 \pm 0.1 \;, \tag{22}$$

where $(\nu_\mu : \nu_e)_{\text{MC}}$ is the $\nu_\mu : \nu_e$ ratio expected on the basis of a Monte Carlo simulation. In addition, it is found that the quantity R depends on the direction from which the neutrinos are coming: For upward-going neutrinos, which must have been produced in the atmosphere on the side of the earth opposite to where the detector is located, and then traveled $\sim 10^4$ km, the diameter of the earth, to reach the detector, R has an anomalously low value. But for downward-going neutrinos, which must have been produced in the atmosphere just above the detector and traveled only $\sim$ 10 km to reach it, R is consistent with unity [22].

The atmospheric neutrino results have been interpreted as $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_e$ oscillation, described by an expression like that of Eq. (11). To accommodate the fact that the upward-going neutrinos oscillate, making R anomalously low, we must have $[1.27\Delta M^2(\text{eV}^2)L(\text{km})/E(\text{GeV})] \gtrsim 1$ when $L \sim 10^4$ km and $E \sim 1$ GeV, a typical energy for the neutrinos studied. This requires $\Delta M^2 \gtrsim 10^{-4}$ eV^2. To accommodate the fact that the downward-going neutrinos do not oscillate (since for them R is not anomalous), we must have $[1.27\Delta M^2(\text{eV}^2)L(\text{km})/E(\text{GeV})] \ll 1$ when $L \sim 10$ km and $E \sim 1$ GeV. This requires $\Delta M^2 \lesssim 10^{-2}$ eV^2. Thus, the favored ΔM^2 range is

$$10^{-4} \lesssim \Delta M^2 \lesssim 10^{-2}\ \text{eV}^2 \;. \tag{23}$$

The size of the observed effect implies that the mixing angle is near maximal:

$$\sin^2 2\theta \approx 1 \;. \tag{24}$$

In view of a recent bound on $\nu_e \leftrightarrow \nu_\mu$ oscillation from the CHOOZ reactor experiment [23], the $\nu_\mu \to \nu_\tau$ interpretation of the atmospheric neutrino data is more likely than the $\nu_\mu \to \nu_e$ interpretation.

The LSND experiment [24] has studied neutrinos from stopped positively-charged pions, which decay via the chain

$$\begin{array}{l} \pi^+ \to \mu^+\nu_\mu \\ \qquad \hookrightarrow e^+\nu_e\overline{\nu}_\mu \end{array} \tag{25}$$

We note that this chain does not produce $\overline{\nu}_e$, but an excess of $\overline{\nu}_e$ over expected background is reported by the experiment. This excess is interpreted as arising from oscillation of the $\overline{\nu}_\mu$ which the chain does produce into $\overline{\nu}_e$. Since the experiment has $L(\text{km})/E(\text{GeV}) \sim 1$, the implied mass splitting is $\Delta M^2 \gtrsim 1$ eV^2.

More recently, the same experiment has studied the neutrinos from the decay

$$\pi^+ \to \mu^+\nu_\mu \tag{26}$$

of positively-charged pions in flight. This decay does not produce ν_e, but the experiment reports a ν_e signal above background [25]. This signal is interpreted as coming from $\nu_\mu \to \nu_e$ oscillation. The regions of ΔM^2 and $\sin^2 2\theta$ favored by the stopped pion and decay-in-flight data are consistent [25,26].

Suppose we assume that the behavior of the solar, atmospheric, and LSND neutrinos are all to be understood in terms of neutrino oscillation. What neutrino masses are then suggested?

If there are only three neutrinos of definite flavor, ν_e, ν_μ, and ν_τ, made up out of just three neutrinos of definite mass, ν_1, ν_2, and ν_3, then there are only three mass splittings ΔM^2_{ij}, and they obviously satisfy

$$\begin{aligned} &\Delta M^2_{12} + \Delta M^2_{23} + \Delta M^2_{31} = \\ &(M_1^2 - M_2^2) + (M_2^2 - M_3^2) + (M_3^2 - M_1^2) = 0\,. \end{aligned} \tag{27}$$

Now, the ΔM^2 required by the MSW explanation of the solar neutrino data is $\sim 10^{-5}$ eV^2, Eq. (21), and that required by the vacuum oscillation explanation is only 10^{-10} eV^2. The ΔM^2 required by the vacuum oscillation interpretation of the atmospheric neutrino anomaly is $\sim 10^{-(2-4)}$eV^2, Eq. (23). Finally, the ΔM^2 favored by the vacuum oscillation explanation of the LSND data is $\gtrsim 1$ eV^2. Since the ΔM^2 values required to explain the solar, atmospheric, and LSND effects are of three different orders of magnitude, there is no way these three ΔM^2 values can add up to zero, as demanded by Eq. (27). Thus, it appears that one cannot explain all three of the existing hints of neutrino oscillation without introducing a fourth neutrino. Since this neutrino is known to make no contribution to the width of the Z^0 [27], it must be a neutrino which does not participate in the normal weak interactions—a "sterile" neutrino.

Despite this argument, interesting attempts have been made to make do with just three neutrinos. In one of these [28], there is a neutrino mass hierarchy of the sort described before Eq. (16), with $\Delta M^2_{32} \approx \Delta M^2_{31} \gg \Delta M^2_{21}$. The large mass splitting, ΔM^2_{32}, is taken to be ~ 0.4 eV^2, and the small one, ΔM^2_{21}, to be $\sim$ (3–10) $\times\, 10^{-5}$eV^2. The LSND results are interpreted as $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ oscillation governed by the large mass splitting. The solar neutrino observations are explained in terms of an MSW $\nu_e \to \nu_\mu$ conversion governed by the small mass splitting. The atmospheric neutrino anomaly, which appears naively to require an intermediate ΔM^2, is explained as a combination of oscillation effects involving both the large ΔM^2_{32} and the small ΔM^2_{21}. This scheme does not quite fit all the data, but it is intriguingly close.

If one assumes that a sterile neutrino cannot be avoided, then all three hints of neutrino oscillation can be accommodated, for example, with the following four neutrinos: A nearly degenerate pair, ν_3, ν_2, with $M_3 \approx M_2 \sim 1$ eV, a lighter neutrino ν_1, with $M_1 \sim 3 \times 10^{-3}$ eV, and a sterile neutrino ν_s much lighter than ν_1 [29]. The flavor neutrinos ν_τ and ν_μ are each 50–50 mixtures of ν_3 and ν_2, in accord with the suggestion from the atmospheric neutrino data that ν_τ and ν_μ are maximally mixed. The ν_e is dominantly ν_1. The mass splitting $M_3^2 - M_2^2$ is chosen to be $\lesssim 10^{-2}$eV^2 to facilitate the $\nu_\mu \to \nu_\tau$ oscillation interpretation of the atmospheric anomaly. The splitting $M_1^2 - M_s^2 \approx M_1^2 \sim 10^{-5}$ eV^2 allows us to interpret the solar neutrino observations as reflecting MSW conversion of ν_e to the sterile ν_s. The splitting $M_3^2 - M_1^2 \approx M_2^2 - M_1^2 \sim 1$ eV^2 enables us to explain the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ oscillation.

The existing hints of neutrino oscillation, and the possible neutrino-mass scenarios which they suggest, will be probed in future neutrino experiments.

In addition to the ν_e, ν_μ, and ν_τ sections, the *Review of Particle Physics* includes sections on "Number of Light Neutrino Types," "Heavy Lepton Searches," and "Searches for Massive Neutrinos and Lepton Mixing."

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$\boxed{\nu_e}$ $J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrino properties above.

Written April 1996 by D.E. Groom (LBNL).

These limits apply to ν_1, the primary mass eigenstate in ν_e. They would also apply to any other ν_j which mixes strongly in ν_e and has sufficiently small mass that it can occur in the respective decay. The neutrino mass may be of a Dirac or Majorana type; the former conserves total lepton number while the latter violates it. Either would violate lepton family number, since nothing forces the neutrino mass eigenstates to coincide with the neutrino interaction eigenstates. For limits on a Majorana ν_e mass, see the section on "Searches for Massive Neutrinos and Lepton Mixing," part (C), entitled "Searches for Neutrinoless Double-β Decay."

The square of the neutrino mass $m^2_{\nu_e}$ is measured in tritium beta decay experiments by fitting the shape of the beta spectrum near the endpoint; results are given in one of the tables in this section. In many experiments, it has been found to be significantly negative. In the 1994 edition of this *Review*, it was noted that the combined probability of a positive result was 3.5%. The problem has been exacerbated by the precise and careful experiments reported in two new papers (BELESEV 95 and STOEFFL 95). Both groups conclude that unknown effects cause the accumulation of events in the electron spectrum near its end point. If the fitting hypothesis does not account for this, unphysical values for $m^2_{\nu_e}$ are obtained. BELESEV 95 obtain their value for $m^2_{\nu_e}$ and limit for m_{ν_e} (4.35 eV at 95% CL) under the assumption that a certain narrow region is free of both high-energy and low-energy anomalies. Including the endpoint accumulation (they find no low-energy anomaly), STOEFFL 95 find a value for $m^2_{\nu_e}$ which is more than 5 standard deviations negative, and report a Bayesian limit of 7 eV for m_{ν_e} which is obtained by setting $m^2_{\nu_e} = 0$. Given the status of the tritium results, we find no clear way to set a meaningful limit on m_{ν_e}. On the other hand, a mass as large as 10–15 eV would probably cause detectable spectrum distortions near the endpoint.

The spread of arrival times of the neutrinos from SN 1987A, coupled with the measured neutrino energies, should provide a simple time-of-flight limit on m_{ν_e}. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The LOREDO 89 limit (23 eV) is among the most conservative and involves few assumptions; as such, it is probably a safe limit. We list this limit below as "used," but conclude that a limit about half this size is justified by the tritium decay experiments.

ν_e MASS

Most of the data from which these limits are derived are from β^- decay experiments in which a $\overline{\nu}_e$ is produced, so that they really apply to $m_{\overline{\nu}_1}$. Assuming *CPT* invariance, a limit on $m_{\overline{\nu}_1}$ is the same as a limit on m_{ν_1}. Results from studies of electron capture transitions, given below "$m_{\nu_1} - m_{\overline{\nu}_1}$", give limits on m_{ν_1} itself. OUR EVALUATION of the present status of the tritium decay experiments is discussed in the above minireview.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 15	**OUR EVALUATION**			
< 23		LOREDO 89	ASTR	SN 1987A
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.35	95	[1] BELESEV 95	SPEC	^{3}H β decay
< 12.4	95	[2] CHING 95	SPEC	^{3}Hβ decay
< 92	95	[3] HIDDEMANN 95	SPEC	^{3}H β decay
$15\ ^{+32}_{-15}$		HIDDEMANN 95	SPEC	^{3}H β decay
< 19.6	95	KERNAN 95	ASTR	SN 1987A
< 7.0	95	[4] STOEFFL 95	SPEC	^{3}H β decay
<460	68	[5] YASUMI 94	CNTR	*e* capture in ^{163}Ho
< 7.2	95	[6] WEINHEIMER 93	SPEC	^{3}H β decay
< 11.7	95	[7] HOLZSCHUH 92B	SPEC	^{3}H β decay
< 13.1	95	[8] KAWAKAMI 91	SPEC	^{3}H β decay
< 9.3	95	[9] ROBERTSON 91	SPEC	^{3}H β decay
< 14	95	AVIGNONE 90	ASTR	SN 1987A
< 16		SPERGEL 88	ASTR	SN 1987A
17 to 40		[10] BORIS 87	SPEC	$\overline{\nu}_e$, ^{3}Hβ decay

[1] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. A fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly) plus a monochromatic line 7–15 eV below the endpoint yields $m^2_\nu = -4.1 \pm 10.9$ eV^2, leading to this Bayesian limit.

[2] CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of m^2_ν is given.

[3] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. Bayesian limit calculated from the weighted mean $m^2_\nu = 221 \pm 4244$ eV^2 from the two runs listed below.

[4] STOEFFL 95 (LLNL) result is the Bayesian limit obtained from the m^2_ν errors given below but with m^2_ν set equal to 0. The anomalous endpoint accumulation leads to a value of m^2_ν which is negative by more than 5 standard deviations.

[5] The YASUMI 94 (KEK) limit results from their measurement $m_\nu = 110^{+350}_{-110}$ eV.

[6] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[7] HOLZSCHUH 92B (Zurich) result is obtained from the measurement $m^2_\nu = -24 \pm 48 \pm 61$ (1σ errors), in eV^2, using the PDG prescription for conversion to a limit in m_ν.

[8] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid. This result is the Bayesian limit obtained from the m^2_ν limit with the errors combined in quadrature. This was also done in ROBERTSON 91, although the authors report a different procedure.

[9] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m^2 is only 3% if statistical and systematic error are combined in quadrature.

[10] See also comment in BORIS 87B and erratum in BORIS 88.

ν_e MASS SQUARED

The tritium experiments actually measure mass squared. A combined limit on mass must therefore be obtained from the weighted average of the results shown here. The recent results are in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88, erratum)] that m_{ν_1} lies between 17 and 40 eV. The BORIS 87 result is excluded because of the controversy over the possibly large unreported systematic errors; see BERGKVIST 85B, BERGKVIST 86, SIMPSON 84, and REDONDO 89. However, the average for the new experiments given below implies only a 3.5% probability that m^2 is positive. See HOLZSCHUH 92 for a review of the recent direct m_{ν_1} measurements.

VALUE (eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
− 27 ± 20	**OUR AVERAGE**	Error includes scale factor of 4.2. See the ideogram below.		
− 22 ± 4.8		[11] BELESEV 95	SPEC	^{3}H β decay
−130 ± 20 ± 15	95	[12] STOEFFL 95	SPEC	^{3}H β decay
− 31 ± 75 ± 48		[13] SUN 93	SPEC	^{3}Hβ decay
− 39 ± 34 ± 15		[14] WEINHEIMER 93	SPEC	^{3}H β decay
− 24 ± 48 ± 61		[15] HOLZSCHUH 92B	SPEC	^{3}H β decay
− 65 ± 85 ± 65		[16] KAWAKAMI 91	SPEC	^{3}H β decay
−147 ± 68 ± 41		[17] ROBERTSON 91	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-129 ± 6010		[18] HIDDEMANN 95	SPEC	^{3}H β decay
313 ± 5994		[18] HIDDEMANN 95	SPEC	^{3}H β decay

[11] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. This value comes from a fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly), including the effects of an apparent peak 7–15 eV below the endpoint.

[12] STOEFFL 95 (LLNL) uses a gaseous source of molecular tritium. An anomalous pileup of events at the endpoint leads to the negative value for m^2_ν. The authors acknowledge that "the negative value for the best fit of m^2_ν has no physical meaning" and discuss possible explanations for this effect.

[13] SUN 93 uses a tritiated hydrocarbon source. See also CHING 95.

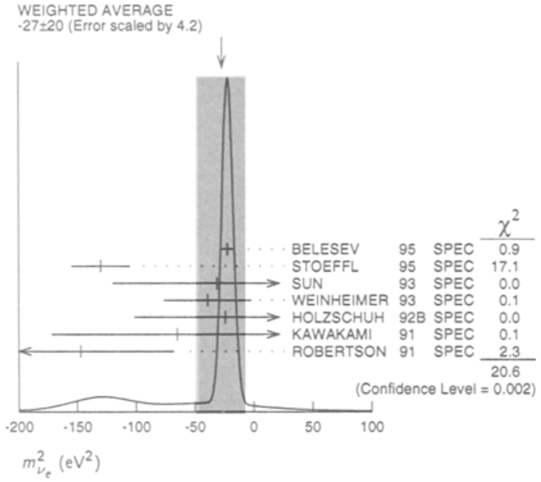
[14] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[15] HOLZSCHUH 92B (Zurich) source is a monolayer of tritiated hydrocarbon.

[16] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid.

[17] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m^2_ν is only 3% if statistical and systematic error are combined in quadrature.

[18] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. They quote measurements from two data sets.



$m_{\nu_1} - m_{\overline{\nu}_1}$

These are measurement of m_{ν_1} (in contrast to $m_{\overline{\nu}_1}$, given above). The masses can be different for a Dirac neutrino in the absense of *CPT* invariance. The test is not very strong.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 225	95	SPRINGER 87	CNTR	ν, ^{163}Ho
< 550	68	YASUMI 86	CNTR	ν, ^{163}Ho
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.5×10^5	90	CLARK 74	ASPK	K_{e3} decay
<4100	67	BECK 68	CNTR	ν, ^{22}Na

ν_1 CHARGE

VALUE (units: electron charge)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<2 \times 10^{-15}$	[19] BARBIELLINI 87	ASTR	SN 1987A
$<1 \times 10^{-13}$	BERNSTEIN 63	ASTR	Solar energy losses

[19] Precise limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field.

ν_1 MEAN LIFE

VALUE (s)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[20] COWSIK 89	ASTR	m_ν = 1–50 MeV
		[21] RAFFELT 89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[22] RAFFELT 89B	ASTR	
>278	90	[23] LOSECCO 87B	IMB	
$> 1.1 \times 10^{25}$		[24] HENRY 81	ASTR	m_ν= 16–20 eV
$> 10^{22}$–10^{23}		[25] KIMBLE 81	ASTR	m_ν= 10–100 eV

[20] COWSIK 89 use observations of supernova SN 1987A to set the limit for the lifetime of a neutrino with $1 < m < 50$ MeV decaying through $\nu_H \rightarrow \nu_1 ee$ to be $\tau > 4 \times 10^{15} \exp(-m/5 \text{ MeV})$ s.

[21] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV^3 (based on $\overline{\nu}_e e^-$ cross sections). The bound is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.

[22] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV^3.

[23] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.

[24] HENRY 81 uses UV flux from clusters of galaxies to find limit for radiative decay.

[25] KIMBLE 81 uses extreme UV flux limits.

ν_1 (MEAN LIFE) / MASS

VALUE (s/eV)	CL%	DOCUMENT ID	TECN	COMMENT
$\mathbf{> 7 \times 10^9}$		[26] RAFFELT 85	ASTR	
>300	90	[27] REINES 74	CNTR	$\overline{\nu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$> 2.8 \times 10^{15}$		[28,29] BLUDMAN 92	ASTR	$m_\nu < 50$ eV
> 6.4	90	[30] KRAKAUER 91	CNTR	$\overline{\nu}$ at LAMPF
$> 6.3 \times 10^{15}$		[29,31] CHUPP 89	ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$		[29] KOLB 89	ASTR	$m_\nu < 20$ eV
$> 8.3 \times 10^{14}$		[32] VONFEILIT... 88	ASTR	
> 22	68	[33] OBERAUER 87		$\overline{\nu}_R$ (Dirac)
> 38	68	[33] OBERAUER 87		$\overline{\nu}$ (Majorana)
> 59	68	[33] OBERAUER 87		$\overline{\nu}_L$ (Dirac)
> 30	68	KETOV 86	CNTR	$\overline{\nu}$ (Dirac)
> 20	68	KETOV 86	CNTR	$\overline{\nu}$ (Majorana)
$> 2 \times 10^{21}$		[34] STECKER 80	ASTR	m_ν= 10–100 eV

[26] RAFFELT 85 limit is from solar x- and γ-ray fluxes. Limit depends on ν flux from pp, now established from GALLEX and SAGE to be > 0.5 of expectation.

[27] REINES 74 looked for ν_e of nonzero mass decaying to a neutral of lesser mass + γ. Used liquid scintillator detector near fission reactor. Finds lab lifetime $6. \times 10^7$ s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit $6. \times 10^7$ s REINES 74 assumed that the full $\overline{\nu}_e$ reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (VOGEL 84). If so, OBERAUER 87 may be comparable or better.

[28] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[29] Nonobservation of γ's in coincidence with ν's from SN 1987A.

[30] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.3a^2 + 9.8a + 15.9)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[31] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[32] Model-dependent theoretical analysis of SN 1987A neutrinos.

[33] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.

[34] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$|(v - c)/c|$ ($v \equiv \nu_1$ VELOCITY)

Expected to be zero for massless neutrino, but tests also whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID	TECN	COMMENT
<1	17	[35] STODOLSKY 88	ASTR	SN 1987A
<0.2		[36] LONGO 87	ASTR	SN 1987A

[35] STODOLSKY 88 result based on <10 hr between $\overline{\nu}_e$ detection in IMB and KAMI detectors and beginning of light signal. Inclusion of the problematic 5 neutrino events from FREJ (four hours later) does not change the result.

[36] LONGO 87 argues that uncertainty between light and neutrino transit times is ±3 hr, ignoring FREJUS events.

ν_1 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_1} < 7.3$ eV, it follows that for the extended standard electroweak theory, $\mu(\nu_1) < 2.3 \times 10^{-18}\ \mu_B$. Current experiments are not yet challenging this limit. There is considerable controversy over the validity of many of the claimed upper limits on the magnetic moment from the astrophysical data. For example, VOLOSHIN 90 states that "in connection with the astrophysical limits on μ_ν, ... there is by now a general consensus that contrary to the initial claims (BARBIERI 88, LATTIMER 88, GOLDMAN 88, NOTZOLD 88), essentially no better than quoted limits (from previous constraints) can be derived from detection of the neutrino flux from the supernova SN1987A." See VOLOSHIN 88 and VOLOSHIN 88C.

VALUE ($10^{-10}\ \mu_B$)	CL%	DOCUMENT ID	TECN	COMMENT
< 1.8	90	[37] DERBIN 94	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.62		[38] ELMFORS 97	COSM	Depolarization in early universe plasma
< 3.2	90	[39] GOVAERTS 96		
< 0.003–0.0005		[40] GOYAL 95		SN 1987A
< 7.7	95	MOURAO 92	ASTR	HOME/KAM2 ν rates
< 2.4	90	[41] VIDYAKIN 92	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
<10.8	90	[42] KRAKAUER 90	CNTR	LAMPF $\nu_e e \rightarrow \nu_e e$
< 0.02		[43] RAFFELT 90	ASTR	Red giant luminosity
< 0.1		[44] RAFFELT 89B	ASTR	Cooling helium stars
< 0.02–0.08		[44,45,46] BARBIERI 88	ASTR	SN 1987A
		[47] FUKUGITA 88	COSM	Primordial magn. fields
< 0.01		[45,46,48] GOLDMAN 88	ASTR	SN 1987A
< 0.005		[44,46] LATTIMER 88	ASTR	SN 1987A
≤ 0.015		[44,46] NOETZOLD 88	ASTR	SN 1987A
≤ .3		[44] RAFFELT 88B	ASTR	He burning stars
< 0.11		[44] FUKUGITA 87	ASTR	Cooling helium stars
< 0.4		LYNN 81	ASTR	
< 0.1–0.2		MORGAN 81	COSM	^{4}He abundance
< 0.85		BEG 78	ASTR	Stellar plasmons
< 0.6		[49] SUTHERLAND 76	ASTR	Red giants + degen. dwarfs
< 1		BERNSTEIN 63	ASTR	Solar cooling
<14		COWAN 57	CNTR	Reactor $\overline{\nu}_e$

[37] DERBIN 94 supersedes DERBIN 93.

[38] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[39] GOVAERTS 96 limit is on $\sqrt{\Sigma \mu\nu_\ell^2}$, based on limits on 2ν decay of ortho-positronium.

[40] GOYAL 95 assume that helicity flip via μ_ν would result in faster cooling and hence shorter burst from SN1987A. Limit is based on the assumed presence of a pion condensate or quark core in the remanant.

[41] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[42] KRAKAUER 90 experiment fully reported in ALLEN 93.

[43] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[44] Significant dependence on details of stellar models.

[45] A limit of 10^{-13} is obtained with even more model-dependence.

[46] These papers have assumed that the right-handed neutrino is inert; see BARBIERI 88B.

[47] FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by $\mu < 10^{-16}\ [10^{-9}\ G/B_0]$ where B_0 is the present-day intergalactic field strength.

[48] Some dependence on details of stellar models.

[49] We obtain above limit from SUTHERLAND 76 using their limit $f < 1/3$.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent (see LEE 77C). It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	CL%	DOCUMENT ID	TECN	COMMENT
0.9±2.7		ALLEN 93	CNTR	LAMPF $\nu_e e \rightarrow \nu_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.3	95	MOURAO 92	ASTR	HOME/KAM2 ν rates
<7.3	90	[50] VIDYAKIN 92	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
1.1±2.3		ALLEN 91	CNTR	Repl. by ALLEN 93
		[51] GRIFOLS 89B	ASTR	SN 1987A

[50] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[51] GRIFOLS 89B sets a limit of $\langle r^2 \rangle < 0.2 \times 10^{-32}$ cm^2 for right-handed neutrinos.

ν_e REFERENCES

ELMFORS	97	NP B503 3	P. Elmfors, K. Enqvist, G. Raffelt, G. Sigl	
GOVAERTS	96	PL B381 451	+Van Caillie	(LOUV)
BELESEV	95	PL B350 263	+Bleule, Geraskin, Golubev+	(INRM, KIAE)
CHING	95	IJMP A10 2841	+Ho, Liang, Mao, Chen, Sun	(CST, BEIJT, CIAE)
GOYAL	95	PL B346 312	+Dutta, Choudhury	(DELH)
HIDDEMANN	95	JP G21 639	+Daniel, Schwentker	(MUNT)
KERNAN	95	NP B437 243	+Krauss	(CASE)
STOEFFL	95	PRL 75 3237	+Decman	(LLNL)
DERBIN	94	PAN 57 222		(PNPI)
		Translated from YAF 57 236.		
YASUMI	94	PL B334 229	+Maezawa, Shima, Inagaki+	(KEK, TSUK, KYOT+)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
DERBIN	93	JETPL 57 768	+Chernyi, Popeko, Muratova+	(PNPI)
		Translated from ZETFP 57 755.		
SUN	93	CJNP 15 261	+Liang, Chen, Si+	(CIAE, CST, BEIJT)
WEINHEIMER	93	PL B300 210	+Przyrembel, Backe+	(MANZ)
BLUDMAN	92	PR D45 4720		(CFPA)
HOLZSCHUH	92	RPP 55 1035		(ZURI)
HOLZSCHUH	92B	PL B287 381	+Fritschi, Kuendig	(ZURI)
MOURAO	92	PL B285 364	+Pulido, Ralston	(LISB, LISBT, CERN, KANS)
VIDYAKIN	92	JETPL 55 206	+Vyrodov, Gurevich, Koslov+	(KIAE)
		Translated from ZETFP 55 212.		
ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
KAWAKAMI	91	PL B256 105	+Kato, Ohshima+	(INUS, TOHOK, TINT, KOBE, KEK)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
ROBERTSON	91	PRL 67 957	+Bowles, Stephenson, Wark, Wilkerson, Knapp	(LASL, LLL)
AVIGNONE	90	PR D41 682	+Collar	(SCUC)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
VOLOSHIN	90	NP B (Proc. Suppl) 19 433		(ITEP)
Neutrino 90 Conference				
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
COWSIK	89	PL B218 91	+Schramm, Hoflich	(WUSL, TATA, CHIC, MPIM)
GRIFOLS	89B	PR D40 3819	+Masso	(BARC)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
LOREDO	89	ANYAS 571 601	+Lamb	(CHIC)
RAFFELT	89	PR D39 2066		(PRIN, UCB)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
REDONDO	89	PR C40 368	+Robertson	(LANL)
BARBIERI	88	PRL 61 27	+Mohapatra	(PISA, UMD)
BARBIERI	88B	PL B213 69	+Mohapatra, Yanagida	(PISA, UMD, MICH)
BORIS	88	PRL 61 245 erratum	+Golutvin, Laptin+	(ITEP, ASCI)
FUKUGITA	88	PRL 60 879	+Notzold, Raffelt, Silk	(KYOTU, MPIM, UCB)
GOLDMAN	88	PRL 60 1789	+Aharanov, Alexander, Nussinov	(TELA)
LATTIMER	88	PRL 61 23	+Cooperstein	(STON, BNL)
Also	88B	PRL 61 2633 erratum	Lattimer, Cooperstein	(STON, BNL)
NOETZOLD	88	PR D38 1658		(MPIM)
NOTZOLD	88	PR D38 1658		(MPIM)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)
SPERGEL	88	PL B200 366	+Bahcall	(IAS)
STODOLSKY	88	PL B201 353		(MPIM)
VOLOSHIN	88	PL B209 360		(ITEP)
Also	88B	JETPL 47 501	Voloshin	(ITEP)
		Translated from ZETFP 47 421.		
VOLOSHIN	88C	JETPL 68 690		(ITEP)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
BARBIELLINI	87	Nature 329 21	+Cocconi	(CERN)
BORIS	87	PRL 58 2019	+Golutvin, Laptin+	(ITEP, ASCI)
Also	88	PRL 61 245 erratum	Boris, Golutvin, Laptin+	(ITEP, ASCI)
BORIS	87B	JETPL 45 333	+Golutvin, Laptin+	(ITEP)
		Translated from ZETFP 45 267.		
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTU, TOKY)
LONGO	87	PR D36 3276	M.J. Longo	(MICH)
LOSECCO	87B	PR D35 2073	+Bionta, Blewitt, Bratton+	(IMB Collab.)
OBERAUER	87	PL B198 113	+von Feilitzsch, Mossbauer	(MUNT)
SPRINGER	87	PR A35 679	+Bennet, Baisden+	(LLNL)
BERGKVIST	86	Moriond Conf., Vol. M48, 465		(STOH)
KETOV	86	JETPL 44 146	+Klimov, Nikolaev, Mikaelyan+	(KIAE)
		Translated from ZETFP 44 114.		
YASUMI	86	PL B181 169	+Ando+	(KEK, OSAK, TOHOK, TSUK, KYOT, INUS+)
BERGKVIST	85B	PL 159B 408		(STOH)
RAFFELT	85	PR D31 3002		(MPIM)
KYULDJIEV	84	NP B243 387		(SOFI)
SIMPSON	84	PR D30 1110		(GUEL)
VOGEL	84	PR D30 1505	P. Vogel	
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
MORGAN	81	PL 102B 247	Morgan	(SUSS)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
LUBIMOV	80	PL 94B 266	+Novikov, Nozik, Tretyakov, Kosik	(ITEP)
Also	80	SJNP 32 154	Kozik, Lubimov, Novikov+	(ITEP)
		Translated from YAF 32 301.		
Also	81	JETP 54 616	Lubimov, Novikov, Nozik+	(ITEP)
		Translated from ZETF 81 1158.		
STECKER	80	PRL 45 1460		(NASA)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
LEE	77C	PR D16 1444	+Shrock	(STON)
SUTHERLAND	76	PR D13 2700	+Ng, Flowers+	(PENN, COLU, NYU)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
REINES	74	PRL 32 180	+Sobel, Gurr	(UCI)
Also	78	Private Comm.	Barnes	(PURD)
BECK	68	ZPHY 216 229	+Daniel	(MPIH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)
COWAN	57	PR 107 528	+Reines	(LANL)

ν_μ

$J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_μ MASS

Applies to ν_2, the primary mass eigenstate in ν_μ. Would also apply to any other ν_j which mixes strongly in ν_μ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.) Results based upon an obselete pion mass are no longer shown; they were in any cass less restrive than ASSAMAGAN 96.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.17	90	[1] ASSAMAGAN	96	SPEC	$m^2 = -0.016 \pm 0.023$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15		[2] DOLGOV	95	COSM	Nucleosynthesis
<0.48		[3] ENQVIST	93	COSM	Nucleosynthesis
<0.003		[4,5] MAYLE	93	ASTR	SN 1987A cooling
< 0.025–0.030		[5,6] BURROWS	92	ASTR	SN 1987A cooling
<0.3		[7] FULLER	91	COSM	Nucleosynthesis
<0.42		[7] LAM	91	COSM	Nucleosynthesis
< 0.028–0.15		[8] NATALE	91	ASTR	SN 1987A
<0.028		[5] GANDHI	90	ASTR	SN 1987A
<0.014		[5,9] GRIFOLS	90B	ASTR	SN 1987A
<0.06		[5,10] GAEMERS	89		SN 1987A
<0.50	90	[11] ANDERHUB	82	SPEC	$m^2 = -0.14 \pm 0.20$
<0.65	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

[1] ASSAMAGAN 96 measurement of p_μ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m^2_\nu = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m_2 = -0.143 \pm 0.024$ MeV^2. Replaces ASSAMAGAN 94.

[2] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below $T_{\rm QCD}$ for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

[3] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[4] MAYLE 93 recalculates cooling rate enhancement by escape of wrong-helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.

[5] There would be an increased cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu} + m^2_{\nu_\tau}}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.

[6] BURROWS 92 limit for Dirac neutrinos only.

[7] Assumes neutrino lifetime >1 s. For Dirac neutrinos only. See also ENQVIST 93.

[8] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[9] GRIFOLS 90B estimated error is a factor of 3.

[10] GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.

[11] ANDERHUB 82 kinematics is insensitive to the pion mass.

$m_{\nu_2} - m_{\overline{\nu}_2}$

Test of *CPT* for a Dirac neutrino. (Not a very strong test.)

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.45	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

ν_2 (MEAN LIFE) / MASS

These limits often apply to ν_τ (ν_3) also.

VALUE (s/eV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
>15.4	90		[12] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$> 2.8 \times 10^{15}$			[13,14] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
none $10^{-12} - 5 \times 10^4$			[15] DODELSON	92	ASTR	m_ν=1–300 keV
$> 6.3 \times 10^{15}$			[14,16] CHUPP	89	ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$			[14] KOLB	89	ASTR	$m_\nu < 20$ eV
$> 3.3 \times 10^{14}$			[17,18] VONFEILIT...	88	ASTR	
> 0.11	90	0	[19] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
			[20] HENRY	81	ASTR	m_ν= 16–20 eV
			[21] KIMBLE	81	ASTR	m_ν= 10–100 eV
			[22] REPHAELI	81	ASTR	m_ν= 30–150 eV
			[23] DERUJULA	80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[24] STECKER	80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[19] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
$> 1.7 \times 10^{-2}$	90	0	[19] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$> 2.2 \times 10^{-3}$	90	0	[19] BARNES	77	DBC	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[19] BELLOTTI	76	HLBC	ν, CERN GGM
$> 1.3 \times 10^{-2}$	90	1	[19] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[12] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[13] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[14] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\tau_\nu \rightarrow \gamma X$ branching ratio.

[15] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[16] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[17] Model-dependent theoretical analysis of SN 1987A neutrinos.

[18] Limit applies to ν_τ also.

[19] These experiments look for $\nu_\mu \rightarrow \nu_e\gamma$ or $\overline{\nu}_\mu \rightarrow \overline{\nu}_e\gamma$.

[20] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

[21] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.

[22] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.

[23] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

[24] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$|(v - c)/c|$ ($v \equiv \nu_2$ VELOCITY)

Expected to be zero for massless neutrino, but also tests whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.4	95	9800	KALBFLEISCH 79	SPEC		
<2.0	99	77	ALSPECTOR 76	SPEC	0	>5 GeV ν
<4.0	99	26	ALSPECTOR 76	SPEC	0	<5 GeV ν

ν_2 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_2} < 0.17$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.51 \times 10^{-13}\ \mu_B$.

VALUE ($10^{-10}\ \mu_B$)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 8.5	90	AHRENS 90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
< 7.4	90	[25] KRAKAUER 90	CNTR	LAMPF $(\nu_\mu, \overline{\nu}_\mu)e$ elast.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.62		[26] ELMFORS 97	COSM	Depolarization in early universe plasma
< 3.2	90	[27] GOVAERTS 96		
< 30	90	VILAIN 95B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$
<100	95	[28] DORENBOS... 91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
< 0.02		[29] RAFFELT 90	ASTR	Red giant luminosity
< 0.1		[30] RAFFELT 89B	ASTR	Cooling helium stars
< 0.11		[30,31] FUKUGITA 87	ASTR	Cooling helium stars
< 0.0006		[32] NUSSINOV 87	ASTR	Cosmic EM backgrounds
< 0.4		LYNN 81	ASTR	
< 0.85		[31] BEG 78	ASTR	Stellar plasmons
< 81		[33] KIM 74	RVUE	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
< 1		[34] BERNSTEIN 63	ASTR	Solar cooling

[25] KRAKAUER 90 experiment fully reported in ALLEN 93.

[26] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[27] GOVAERTS 96 limit is on $\sqrt{\Sigma \mu\nu_\ell^2}$, based on limits on 2ν decay of ortho-positronium.

[28] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν_2 magnetic moment is $< 1 \times 10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu}_\mu e$ elastic scattering and assume $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.

[29] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[30] Significant dependence on details of stellar properties.

[31] If $m_{\nu_2} < 10$ keV.

[32] For $m_{\nu_2} = 8$–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m_{\nu_2} > 16$ eV and $< 6 \times 10^{-14}$ for $m_{\nu_2} > 4$ eV.

[33] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.

[34] If $m_{\nu_2} < 1$ keV.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent (see LEE 77C). It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • *We do not use the following data for averages, fits, limits, etc.* • • •				
< |0.6|	90	VILAIN 95B	CHM2	$\nu_\mu e$ elas scat
-1.1 ± 1.0		[35] AHRENS 90	CNTR	$\nu_\mu e$ elas scat
-0.3 ± 1.5		[35] DORENBOS... 89	CHRM	$\nu_\mu e$ elas scat

[35] Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain $1\,\sigma$ errors.

ν_μ REFERENCES

ELMFORS	97	NP B503 3	P. Elmfors, K. Enqvist, G. Raffelt, G. Sigl	
ASSAMAGAN	96	PR D53 6065	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
GOVAERTS	96	PL B381 451	+Van Caillie	(LOUV)
DOLGOV	95	PR D51 4129	+Kainulainen, Rothstein	(MICH, MINN, CERN)
VILAIN	95B	PL B345 115	+Wilquet, Beyer+	(CHARM II Collab.)
ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
DOLGOV	93	PRL 71 476	+Rothstein	(MICH)
ENQVIST	93	PL B301 376	+Uibo	(NORD)
MAYLE	93	PL B317 119	+Schramm, Turner, Wilson	(LLNL, CHIC)
RAJPOOT	93	MPL A8 1179		(CSULB)
BLUDMAN	92	PR D45 4720		(CFPA)
BURROWS	92	PRL 68 3834	+Gandhi, Turner	(ARIZ, CHIC)
DODELSON	92	PRL 68 2572	+Frieman, Turner	(FNAL, CHIC)
ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
DORENBOS...	91	ZPHY C51 142	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GANDHI	91	PL B261 519E (erratum)	+Burrows	(ARIZ)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
AHRENS	90	PR D41 3297	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	Gandhi, Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(ANIK, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTU, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
ANDERHUB	82	PL 114B 76	+Boecklin, Hofer, Kottmann+	(ETH, SIN)
FRANK	81	PR D24 2001	+Burman+	(LASL, YALE, MIT, SACL, SIN+)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
STECKER	80	PRL 45 1460		(NASA)
KALBFLEISCH	79	PRL 43 1361	+Baggett, Fowler+	(FNAL, PURD, BELL)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BARNES	77	PRL 38 1049	+Carmony, Dauwe, Fernandez+	(PURD, ANL)
LEE	77C	PR D16 1444	+Shrock	(STON)
ALSPECTOR	76	PRL 36 837	+	(BNL, PURD, CIT, FNAL, ROCK)
BELLOTTI	76	LNC 17 553	+Cavalli, Fiorini, Rollier	(MILA)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
KIM	74	PR D9 3050	+Mather, Okubo	(ROCH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)

$\boxed{\nu_\tau}$

$J = \frac{1}{2}$

Existence indirectly established from τ decay data combined with ν reaction data. See for example FELDMAN 81. ALBRECHT 92Q rules out $J = 3/2$ by establishing that the ρ^- is not in a pure $H_\rho = -1$ helicity state in $\tau^- \rightarrow \rho^- \nu_\tau$.

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_τ MASS

Applies to ν_3, the primary mass eigenstate in ν_τ. Would also apply to any other ν_j which mixes strongly in ν_τ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for a hypothetical $J \geq 4$, given the ν_e and ν_μ mass limits above.) See also the Listings in the Neutrino Bounds from Astrophysics and Cosmology section.

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 18.2	95		[1] BARATE 98F	ALEP	1991–1995 LEP runs

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 60	95		[2] ANASTASSOV	97 CLEO	E^{ee}_{cm}= 10.6 GeV
< 0.37 or >22			[3] FIELDS	97 COSM	Nucleosynthesis
< 68	95		[4] SWAIN	97 THEO	m_τ, τ_τ, τ partial widths
< 29.9	95		[5] ALEXANDER	96M OPAL	1990–1994 LEP runs
<149			[6] BOTTINO	96 THEO	π, μ, τ leptonic decays
<1 or >25			[7] HANNESTAD	96C COSM	Nucleosynthesis
< 71	95		[8] SOBIE	96 THEO	m_τ, τ_τ, B($\tau^- \to e^- \overline{\nu}_e \nu_\tau$)
< 74	95		[9] AKERS	95D OPAL	$Z \to \tau^+\tau^-$ at LEP
< 24	95	25	[10] BUSKULIC	95H ALEP	1991–1993 LEP runs
< 0.19			[11] DOLGOV	95 COSM	Nucleosynthesis
< 3			[12] SIGL	95 ASTR	SN 1987A
< 0.4 or > 30			[13] DODELSON	94 COSM	Nucleosynthesis
< 0.1 or > 50			[14] KAWASAKI	94 COSM	Nucleosynthesis
155–225			[15] PERES	94 THEO	π,K,μ,τ weak decays
< 75	95		[16] BALEST	93 CLEO	E^{ee}_{cm}= 10.6 GeV
< 32.6	95	113	[17] CINABRO	93 CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
< 0.3 or > 35			[18] DOLGOV	93 COSM	Nucleosynthesis
< 0.74			[19] ENQVIST	93 COSM	Nucleosynthesis
< 0.003			[20,21] MAYLE	93 ASTR	SN 1987A cooling
< 31	95	19	[22] ALBRECHT	92M ARG	E^{ee}_{cm}= 9.4–10.6 GeV
< 0.025–0.030			[21,23] BURROWS	92 ASTR	SN 1987A cooling
< 0.3			[24] FULLER	91 COSM	Nucleosynthesis
< 0.5 or > 25			[25] KOLB	91 COSM	Nucleosynthesis
< 0.42			[24] LAM	91 COSM	Nucleosynthesis
< 0.028–0.15			[26] NATALE	91 ASTR	SN 1987A
< 0.028			[21] GANDHI	90 ASTR	SN 1987A
< 0.014 or > 34			[21,27] GRIFOLS	90B ASTR	SN 1987A
< 0.06			[21,28] GAEMERS	89	SN 1987A

[1] BARATE 98F result based on kinematics of 2939 $\tau^- \to 2\pi^-\pi^+\nu_\tau$ and 52 $\tau^- \to 3\pi^-2\pi^+(\pi^0)\nu_\tau$ decays. If possible 2.5% excited a_1 decay is included in 3-prong sample analysis, limit increases to 19.2 MeV.

[2] ANASTASSOV 97 derive limit by comparing their m_τ measurement (which depends on m_{ν_τ}) to BAI 96 m_τ threshold measurement.

[3] FIELDS 97 limit for a Dirac neutrino. For a Majorana neutrino the mass region < 0.93 or >31 MeV is excluded. These bounds assume N_ν <4 from nucleosynthesis; a wider excluded region occurs with a smaller N_ν upper limit.

[4] SWAIN 97 derive their limit from the Standard Model relationships between the tau mass, lifetime, branching fractions for $\tau^- \to e^-\overline{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$, $\tau^- \to \pi^-\nu_\tau$, and $\tau^- \to K^-\nu_\tau$, and the muon mass and lifetime by assuming lepton universality and using world average values. Limit is reduced to 48 MeV when the CLEO τ mass measurement (BALEST 93) is included; see CLEO's more recent m_{ν_τ} limit (ANASTASSOV 97). Consideration of mixing with a fourth generation heavy neutrino yields $\sin^2\theta_L < 0.016$ (95%CL).

[5] ALEXANDER 96M bound comes from analyses of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \to h^-h^-h^+\nu_\tau$ decays.

[6] BOTTINO 96 assumes three generations of neutrinos with mixing, finds consistency with massless neutrinos with no mixing based on 1995 data for masses, lifetimes, and leptonic partial widths.

[7] HANNESTAD 96C limit is on the mass of a Majorana neutrino. This bound assumes N_ν < 4 from nucleosynthesis. A wider excluded region occurs with a smaller N_ν upper limit. This paper is the corrected version of HANNESTAD 96; see the erratum: HANNESTAD 96B.

[8] SOBIE 96 derive their limit from the Standard Model relationship between the tau mass, lifetime, and leptonic branching fraction, and the muon mass and lifetime, by assuming lepton universality and using world average values.

[9] AKERS 95D bound comes from analysis of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ decay mode.

[10] BUSKULIC 95H bound comes from a two-dimensional fit of the visible energy and invariant mass distribution of $\tau \to 5\pi(\pi^0)\nu_\tau$ decays. Replaced by BARATE 98F.

[11] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits. DOLGOV 96 argues that a possible window near 20 MeV is excluded.

[12] SIGL 95 exclude massive Dirac or Majorana neutrinos with lifetimes between 10^{-3} and 10^8 seconds if the decay products are predominantly γ or e^+e^-.

[13] DODELSON 94 calculate constraints on ν_τ mass and lifetime from nucleosynthesis for 4 generic decay modes. Limits depend strongly on decay mode. Quoted limit is valid for all decay modes of Majorana neutrinos with lifetime greater than about 300 s. For Dirac neutrinos limits change to < 0.3 or > 33.

[14] KAWASAKI 94 excluded region is for Majorana neutrino with lifetime >1000 s. Other limits are given as a function of ν_τ lifetime for decays of the type $\nu_\tau \to \nu_\mu\phi$ where ϕ is a Nambu-Goldstone boson.

[15] PERES 94 used PDG 92 values for parameters to obtain a value consistent with mixing. Reexamination by BOTTINO 96 which included radiative corrections and 1995 PDG parameters resulted in two allowed regions, $m_3 < 70$ MeV and 140 MeV $m_3 < 149$ MeV.

[16] BALEST 93 derive limit by comparing their m_τ measurement (which depends on m_{ν_τ}) to BAI 92 and BACINO 78B m_τ threshold measurements.

[17] CINABRO 93 bound comes from analysis of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \to 2\pi^-\pi^+2\pi^0\nu_\tau$ decay modes.

[18] DOLGOV 93 assumes neutrino lifetime >100 s. For Majorana neutrinos, the low mass limit is 0.5 MeV. KAWANO 92 points out that these bounds can be overcome for a Dirac neutrino if it possesses a magnetic moment. See also DOLGOV 96.

[19] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[20] MAYLE 93 recalculates cooling rate enhancement by escape of wrong-helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.

[21] There would be an increased SN 1987A cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu}+m^2_{\nu_\tau}}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.

[22] ALBRECHT 92M reports measurement of a slightly lower τ mass, which has the effect of reducing the ν_τ mass reported in ALBRECHT 88B. Bound is from analysis of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ mode.

[23] BURROWS 92 limit for Dirac neutrinos only.

[24] Assumes neutrino lifetime >1 s. For Dirac neutrinos. See also ENQVIST 93.

[25] KOLB 91 exclusion region is for Dirac neutrino with lifetime >1 s; other limits are given.

[26] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[27] GRIFOLS 90B estimated error is a factor of 3.

[28] GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.

ν_3 (MEAN LIFE) / MASS

These limits often apply to ν_μ (ν_2) also.

VALUE (s/eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>1 \times 10^{14}$	[29] SIGL	95	ASTR	$m_\nu >$ few MeV
$>2.8 \times 10^{15}$	[30,31] BLUDMAN	92	ASTR	$m_\nu <$ 50 eV
$< 10^{-12}$ or $> 5 \times 10^4$	[32] DODELSON	92	ASTR	m_ν=1–300 keV
	[33] GRANEK	91	COSM	Decaying L^0
	[34] WALKER	90	ASTR	m_ν= 0.03 – ~ 2 MeV
$>6.3 \times 10^{15}$	[31,35] CHUPP	89	ASTR	$m_\nu <$ 20 eV
$>1.7 \times 10^{15}$	[31] KOLB	89	ASTR	$m_\nu <$ 20 eV
	[36] TERASAWA	88	COSM	m_μ= 30–70 MeV
	[37] KAWASAKI	86	COSM	m_ν >10 MeV
	[38] LINDLEY	85	COSM	$m_\nu >$ 10 MeV
	[39] BINETRUY	84	COSM	$m_\nu \sim$ 1 MeV
	[40] SARKAR	84	COSM	m_ν= 10–100 MeV
	[41] HENRY	81	ASTR	m_ν= 16–20 eV
	[42] KIMBLE	81	ASTR	m_ν= 10–100 eV
	[43] REPHAELI	81	ASTR	m_ν= 30–150 eV
	[44] DERUJULA	80	ASTR	m_ν= 10–100 eV
$>2 \times 10^{21}$	[45] STECKER	80	ASTR	m_ν= 10–100 eV
	[46] DICUS	78	COSM	m_ν= 0.5–30 MeV
$<3 \times 10^{-11}$	[47] FALK	78	ASTR	m_ν <10 MeV
	[48] COWSIK	77	ASTR	

[29] SIGL 95 exclude 1 s $\lesssim \tau \lesssim 10^8$ s for MeV-mass τ nuetrinos from SN 1987A decaying radiatively, and eliminates the lower limit using other published results.

[30] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[31] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\tau_\nu \to \gamma X$ branching ratio.

[32] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[33] GRANEK 91 considers heavy neutrino decays to $\gamma\nu_L$ and $3\nu_L$, where m_{ν_L} <100 keV. Lifetime is calculated as a function of heavy neutrino mass, branching ratio into $\gamma\nu_L$, and m_{ν_L}.

[34] WALKER 90 uses SN 1987A γ flux limits after 289 days to find $m_\tau > 1.1 \times 10^{15}$ eV s.

[35] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[36] TERASAWA 88 finds only $10^2 < \tau < 10^4$ allowed for 30–70 MeV ν's from primordal nucleosynthesis.

[37] KAWASAKI 86 concludes that light elements in primordal nucleosynthesis would be destroyed by radiative decay of neutrinos with 10 MeV<m_ν <1 GeV unless $\tau \lesssim 10^4$ s.

[38] LINDLEY 85 considers destruction of cosmologically-produced light elements, and finds $\tau < 2 \times 10^3$ s for 10 MeV <m_ν <100 MeV. See also LINDLEY 79.

[39] BINETRUY 84 finds $\tau < 10^8$ s for neutrinos in a radiation-dominated universe.

[40] SARKAR 84 finds $\tau <$ 20 s at m_ν=10 MeV, with higher limits for other m_ν, and claims that all masses between 1 MeV and 50 MeV are ruled out.

[41] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

[42] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.

[43] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.

[44] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

[45] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at m_ν = 20 eV.

[46] DICUS 78 considers effect of ν decay photons on light-element production, and finds lifetime must be less than "hours." See also DICUS 77.

[47] FALK 78 finds lifetime constraints based on supernova energetics.

[48] COWSIK 77 considers varity of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require $\tau > 10^{23}$ s for $m_\nu \sim 1$ eV. See also COWSIK 79 and GOLDMAN 79.

ν_3 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_3} < 35$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_3) < 1.1 \times 10^{-11}\ \mu_B$.

VALUE (μ_B)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5.4 \times 10^{-7}$	90	[49] COOPER-...	92	BEBC	$\nu_\tau e^- \to \nu_\tau e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4 \times 10^{-6}$	90	ABREU	97J	DLPH	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<3.3 \times 10^{-6}$	90	[50] ACCIARRI	97Q	L3	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<6.2 \times 10^{-11}$		[51] ELMFORS	97	COSM	Depolarization in early universe plasma
$<2.7 \times 10^{-6}$	95	[52] ESCRIBANO	97	RVUE	$\Gamma(Z \to \nu\nu)$ at LEP
$<3.2 \times 10^{-10}$	90	[53] GOVAERTS	96		
$<5.5 \times 10^{-6}$	90	GOULD	94	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$\gtrsim 10^{-8}$		[54] KAWANO	92	ASTR	Primodial ^{4}He abundance
$<5.6 \times 10^{-6}$	90	DESHPANDE	91	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<2 \times 10^{-12}$		[55] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[56] RAFFELT	89B	ASTR	Cooling helium stars
$<4. \times 10^{-6}$	90	[57] GROTCH	88	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<1.1 \times 10^{-11}$		[56,58] FUKUGITA	87	ASTR	Cooling helium stars
$<6 \times 10^{-14}$		[59] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<8.5 \times 10^{-11}$		[58] BEG	78	ASTR	Stellar plasmons

[49] COOPER-SARKAR 92 assume $f_{D_s}/f_\pi = 2$ and D_s, $\overline{D}_s$ production cross section = 2.6 μb to calculate ν_τ flux.

[50] ACCIARRI 97Q result applies to both direct and transition magnetic moments and for q^2=0.

[51] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[52] Applies to absolute value of magnetic moment.

[53] GOVAERTS 96 limit is on $\sqrt{\Sigma \mu\nu_\ell^2}$, based on limits on 2ν decay of ortho-positronium.

[54] KAWANO 92 lower limit is that needed to circumvent ^{4}He production if m_{ν_τ} is between 5 and $\sim$ 30 MeV/c^2.

[55] RAFFELT 90 limit valid if $m_{\nu_3} < 5$ keV. It applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[56] Significant dependence on details of stellar properties.

[57] GROTCH 88 combined data from MAC, ASP, CELLO, and Mark J.

[58] If $m_{\nu_3} < 10$ keV.

[59] For m_{ν_3} = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\tau \to \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m_{\nu_3} < 16$ eV and $< 6 \times 10^{-14}$ for $m_{\nu_3} > 4$ eV.

ν_3 ELECTRIC DIPOLE MOMENT

VALUE (ecm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5.2 \times 10^{-17}$	95	[60] ESCRIBANO	97	RVUE	$\Gamma(Z \to \nu\nu)$ at LEP

[60] Applies to absolute value of electric dipole moment.

ν_3 CHARGE

VALUE (units: electron charge)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4 \times 10^{-4}$	[61] BABU	94	RVUE	BEBC beam dump
$<3 \times 10^{-4}$	[62] DAVIDSON	91	RVUE	SLAC electron beam dump

[61] BABU 94 use COOPER-SARKAR 92 limit on ν_3 magnetic moment to derive quoted result.

[62] DAVIDSON 91 use data from early SLAC electron beam dump experiment to derive charge limit as a function of neutrino mass.

LIMIT ON ν_τ PRODUCTION IN BEAM DUMP EXPERIMENT

VALUE	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[63] DORENBOS...	88	CHRM
	[64] BOFILL	87	CNTR
	[65] TALEBZADEH	87	BEBC
	[66] USHIDA	86C	EMUL
	[67] ASRATYAN	81	HLBC
	[68] FRITZE	80	BEBC

[63] DORENBOSCH 88 is CERN SPS beam dump experiment with the CHARM detector. $\nu_\tau + \overline{\nu}_\tau$ flux is <21% of the total prompt flux at 90% CL.

[64] BOFILL 87 is a Fermilab narrow-band ν beam with a fine-grained neutrino detector.

[65] TALEBZADEH 87 is a CERN SPS beam dump experiment with the BEBC detector. Mixing probability $P(\nu_e \to \nu_\tau)$ <18% at 90% CL.

[66] USHIDA 86C is a Fermilab wide-band ν beam with a hybrid emulsion spectrometer. Mixing probabilities $P(\nu_e \to \nu_\tau) < 7.3\%$ and $P(\nu_\mu \to \nu_\tau) < 0.2\%$ at 90% CL.

[67] ASRATYAN 81 is a Fermilab wide-band $\overline{\nu}$ beam with a 15 foot bubble chamber. Mixing probability $P(\overline{\nu}_\mu \to \overline{\nu}_\tau) < 2.2\%$ at 90% CL.

[68] FRITZE 80 is CERN SPS experiment with BEBC. Neutral-current/charged-current ratio corresponds to R = (prompt-ν_τ-induced events)/(all prompt-ν events) <0.1. Mixing probability $P(\nu_e \to \nu_\tau)$ <0.35 at CL = 90%.

ν_τ REFERENCES

BARATE	98F	EPJ C2 395	R. Barate+	(ALEPH Collab.)
ABREU	97J	ZPHY C74 577	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97Q	PL B412 201	M. Acciarri+	(L3 Collab.)
ANASTASSOV	97	PR D55 2559	+Blinov, Duboscq, Fisher, Fujino+	(CLEO Collab.)
ELMFORS	97	NP B503 3	P. Elmfors, K. Enqvist, G. Raffelt, G. Sigl	
ESCRIBANO	97	PL B395 369	+Masso	(BARC, PARIT)
FIELDS	97	ASP 6 169	+Kainulainen, Olive	(NDAM, MINN)
SWAIN	97	PR D55 R1	+Taylor	(NEAS)
ALEXANDER	96M	ZPHY C72 231	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BAI	96	PR D53 20	+Bardon, Becker-Szendy, Blum+	(BES Collab.)
BOTTINO	96	PR D53 6361	A. Bottino+	
DOLGOV	96	PL B383 193	+Pastor, Valle	(IFIC, VALE)
GOVAERTS	96	PL B381 451	+Van Caillie	(LOUV)
HANNESTAD	96	PRL 76 2848	+Madsen	(AARH)
HANNESTAD	96B	PRL 77 5148 (erratum)	+Madsen	(AARH)
HANNESTAD	96C	PR D54 7894	+Madsen	(AARH)
SOBIE	96	ZPHY C70 383	+Keeler, Lawson	(VICT)
AKERS	95D	ZPHY C65 183	+Alexander, Allison, Anderson+	(OPAL Collab.)
BUSKULIC	95H	PL B349 585	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
DOLGOV	95	PR D51 4129	+Kainulainen, Rothstein	(MICH, MINN, CERN)
SIGL	95	PR D51 1499	+Turner	(FNAL, EFI)
BABU	94	PL B321 140	+Gould, Rothstein	(BART, JHU, MICH)
DODELSON	94	PR D49 5068	+Gyuk, Turner	(FNAL, CHIC, EFI)
GOULD	94	PL B333 545	+Rothstein	(JHU, MICH)
KAWASAKI	94	NP B419 105	+Kernan, Kang+	(OSU)
PERES	94	PR D50 513	O.L.G. Peres, V. Pleitez, Funchal	
BALEST	93	PR D47 R3671	+Daoudi, Ford, Johnson+	(CLEO Collab.)
CINABRO	93	PRL 70 3700	+Henderson, Kinoshita+	(CLEO Collab.)
DOLGOV	93	PRL 71 476	+Rothstein	(MICH)
ENQVIST	93	PL B301 376	+Uibo	(NORD)
MAYLE	93	PL B317 119	+Schramm, Turner, Wilson	(LLNL, CHIC)
RAJPOOT	93	MPL A8 1179		(CSULB)
ALBRECHT	92M	PL B292 221	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	92Q	ZPHY C56 339	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BAI	92	PRL 69 3021	+Bardon, Becker-Szendy, Burnett+	(BES Collab.)
BLUDMAN	92	PR D45 4720		(CFPA)
BURROWS	92	PRL 68 3834	+Gandhi, Turner	(ARIZ, CHIC)
COOPER-...	92	PL B280 153	Cooper-Sarkar, Sarkar, Guy, Venus+	(BEBC WA66 Collab.)
DODELSON	92	PRL 68 2572	+Frieman, Turner	(FNAL, CHIC)
KAWANO	92	PL B275 487	+Fuller, Malaney, Savage	(CIT, UCSD, LLL, RUTG)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
DAVIDSON	91	PR D43 2314	+Campbell, Bailey	(ALBE, TNTO)
DESHPANDE	91	PR D43 943	+Sarma	(OREG, TATA)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GANDHI	91	PL B261 519E (erratum)	+Burrows	(ARIZ)
GRANEK	91	IJMP A6 2387	+McKellar	(MELB)
KOLB	91	PRL 67 533	+Turner, Chakravorty, Schramm	(FNAL, CHIC)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	Gandhi, Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
RAFFELT	90	PRL 64 2856		(MPIM)
WALKER	90	PR D41 689		(HARV)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(ANIK, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
ALBRECHT	88B	PL B202 149	+Binder, Boeckmann+	(ARGUS Collab.)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
GROTCH	88	ZPHY C39 553	+Robinett	(PSU)
TERASAWA	88	NP B302 697	+Kawasaki, Sato	(TOKY)
BOFILL	87	PR D36 3309	+Busza, Eldridge+	(MIT, FNAL, MSU)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTU, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
TALEBZADEH	87	NP B291 503	+Guy, Venus+	(BEBC WA66 Collab.)
KAWASAKI	86	PL B178 71	+Terasawa, Sato	(TOKY)
USHIDA	86C	PRL 57 2897	+Kondo, Tasaka, Park, Song+	(FNAL E531 Collab.)
LINDLEY	85	APJ 294 1		(FNAL)
BINETRUY	84	PL 134B 174	+Girardi, Salati	(LAPP)
SARKAR	84	PL 148B 347	+Cooper	(OXF, CERN)
ASRATYAN	81	PL 105B 301	+Efremenko, Fedotov+	(ITEP, FNAL, SERP, MICH)
FELDMAN	81	SLAC-PUB-2839		(SLAC, STAN)
Santa Cruz APS.				
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FRITZE	80	PL 96B 427		(AACH3, BONN, CERN, LOIC, OXF, SACL)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
STECKER	80	PRL 45 1460		(NASA)
COWSIK	79	PR D19 2219		(TATA)
GOLDMAN	79	PR D19 2215	+Stephenson	(LASL)
LINDLEY	79	MNRAS 188 15P		(SUSS)
BACINO	78B	PRL 41 13	+Ferguson, Nodulman, Slater+	(DELCO Collab.)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
DICUS	78	PR D17 1529	+Kolb, Teplitz, Wagoner	(TEXA, VPI, STAN)
FALK	78	PL 79B 511	+Schramm	(CHIC)
COWSIK	77	PRL 39 784		(MPIM, TATA)
DICUS	77	PRL 39 168	+Kolb, Teplitz	(TEXA, VPI)

OTHER RELATED PAPERS

WEINSTEIN	93	ARNPS 43 457	+Stroynowski	(CIT, SMU)

Number of Light Neutrino Types

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m_\nu < m_Z/2$. The limits are on the number of neutrino families or species, including ν_e, ν_μ, ν_τ

THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

Revised April 1998 by D. Karlen (Carleton University).

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. At the time of this report, the most recent (preliminary) combined analysis of the four LEP experiments [1] included over 16 million visible Z decays. The invisible partial width, Γ_{inv}, is determined from these data by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\text{SM}} = 1.991 \pm 0.001$, is used instead of $(\Gamma_\nu)_{\text{SM}}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}}$$

The combined LEP result is $N_\nu = 2.993 \pm 0.011$.

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. Since this method is much more dependent on the Standard Model, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \to \nu\bar{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background [2], leading to a 95% CL limit of $N_\nu < 4.8$. This process has a much larger cross section at center-of-mass energies near the Z mass and has been measured at LEP by the ALEPH, DELPHI, L3, and OPAL experiments [3]. These experiments have observed several thousand such events, and the combined result is $N_\nu = 3.00 \pm 0.09$.

Experiments at $p\bar{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \to \ell^\pm\nu$ to $Z \to \ell^+\ell^-$ events [4]. This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

References

1. The LEP Collaborations, the LEP Electroweak Working Group, and the SLD Heavy Flavor Group, CERN/PPE/97-154. (Based upon published and preliminary electroweak results).
2. VENUS: K. Abe *et al.*, Phys. Lett. **B232**, 431 (1989);
   ASP: C. Hearty *et al.*, Phys. Rev. **D39**, 3207 (1989);
   CELLO: H.J. Behrend *et al.*, Phys. Lett. **B215**, 186 (1988);
   MAC: W.T. Ford *et al.*, Phys. Rev. **D33**, 3472 (1986);
   MARK J: H. Wu, Ph.D. Thesis, Univ. Hamburg (1986).
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   DELPHI: P. Abreu *et al.*, Z. Phys. **C74**, 577 (1997);
   OPAL: R. Akers *et al.*, Z. Phys. **C65**, 47 (1995);
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Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

VALUE	*DOCUMENT ID*	*TECN*
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.00 ±0.05	[1] LEP 92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \to \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–94 GeV.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
3.07±0.12 OUR AVERAGE			
2.89±0.32±0.19	ABREU 97J	DLPH	1993–1994 LEP runs
3.23±0.16±0.10	AKERS 95C	OPAL	1990–1992 LEP runs
2.68±0.20±0.20	BUSKULIC 93L	ALEP	1990–1991 LEP runs
3.24±0.46±0.22	ADEVA 92	L3	1990 LEP run
3.14±0.24±0.12	ADRIANI 92E	L3	1991 LEP run
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.1 ±0.6 ±0.1	ADAM 96C	DLPH	$\sqrt{s} = 130, 136$ GeV

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
< 4.9	COPI 97	COSM
< 3.6	[2] HATA 97B	COSM
< 4.0	[3] OLIVE 97	COSM
< 4.7	[2] CARDALL 96B	COSM
< 3.9	[3] FIELDS 96	COSM
< 4.5	[2] KERNAN 96	COSM
< 3.6	[4] OLIVE 95	COSM
< 3.3	WALKER 91	COSM
< 3.4	OLIVE 90	COSM
< 4	YANG 84	COSM
< 4	YANG 79	COSM
< 7	STEIGMAN 77	COSM
	PEEBLES 71	COSM
<16	[5] SHVARTSMAN69	COSM
	HOYLE 64	COSM

[2] Limit based on high D/H from quasar absorption systems.

[3] Limit based on high ^{4}He and ^{7}Li.

[4] OLIVE 95 limit assumes the existence of at least three (massless) neutrinos.

[5] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
<20	[6] OLIVE 81C	COSM
<20	[6] STEIGMAN 79	COSM

[6] Limit varies with strength of coupling. See also WALKER 91.

REFERENCES FOR Limits on Number of Light Neutrino Types

ABREU 97J ZPHY C74 577 P. Abreu+ (DELPHI Collab.)
COPI 97 PR D55 3389 C.J. Copi, D.N. Schramm, M.S. Turner (CHIC)
HATA 97B PR D55 540 N. Hata, G. Steigman, S. Bludman+ (OSU, PENN)
OLIVE 97 ASP 7 27 +Thomas (MINN, FLOR)
ADAM 96C PL B380 471 +Adye, Agasi, Ajinenko, Aleksan+ (DELPHI Collab.)
CARDALL 96B APJ 472 435 +Fuller (UCSD)
FIELDS 96 New Ast 1 77 +Kainulainen, Olive+ (NDAM, CERN, MINN, FLOR)
KERNAN 96 PR D54 3681 P.S. Kernan, S. Sarkar (CASE, OXFTP)
AKERS 95C ZPHY C65 47 +Alexander, Allison+ (OPAL Collab.)
OLIVE 95 PL B354 357 +Steigman (MINN, OSU)
BUSKULIC 93L PL B313 520 +De Bonis, Decamp+ (ALEPH Collab.)
ADEVA 92 PL B275 209 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ADRIANI 92E PL B292 463 +Aguilar-Benitez, Ahlen, Akbari, Alcaraz+ (L3 Collab.)
LEP 92 PL B276 247 +ALEPH, DELPHI, L3, OPAL (LEP Collabs.)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
DENEGRI 90 RMP 62 1 +Sadoulet, Spiro (CERN, UCB, SACL)
OLIVE 90 PL B236 454 +Schramm, Steigman, Walker (MINN, CHIC, OSU, HARV)
YANG 84 APJ 281 493 +Turner, Steigman, Schramm, Olive (CHIC, BART)
OLIVE 81 APJ 246 557 +Schramm, Steigman, Turner, Yang+ (CHIC, BART)
OLIVE 81C NP B180 497 +Schramm, Steigman (EFI, BART)
STEIGMAN 79 PRL 43 239 +Olive, Schramm (BART, EFI)
YANG 79 APJ 227 697 +Schramm, Steigman, Rood (CHIC, YALE, VIRG)
STEIGMAN 77 PL 66B 202 +Schramm, Gunn (YALE, CHIC, CIT)
PEEBLES 71 Physical Cosmology (PRIN)
Princeton Univ. Press (1971)
SHVARTSMAN 69 JETPL 9 184 (MOSU)
Translated from ZETFP 9 315.
HOYLE 64 Nature 203 1108 +Tayler (CAMB)

Massive Neutrinos and Lepton Mixing, Searches for

SEARCHES FOR MASSIVE NEUTRINOS

Revised April 1998 by D.E. Groom (LBNL).

Searches for massive neutral leptons and the effects of nonzero neutrino masses are listed here. These results are divided into the following main sections:

A. Heavy neutral lepton mass limits;
B. Sum of neutrino masses;
C. Searches for neutrinoless double-β decay (see the note by P. Vogel on "Searches for neutrinoless double-β decay" preceding this section);
D. Other bounds from nuclear and particle decays;
E. Bounds from particle decays;
F. Solar ν experiments (see the note on "Solar Neutrinos" by K. Nakamura preceding this section);
G. Astrophysical neutrino observations;
H. Reactor $\overline{\nu}_e$ disappearance experiments;
I. Accelerator neutrino appearance experiments;
J. Disappearance experiments with accelerator and radioactive source neutrinos.

Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate section on ν_e, ν_μ, or ν_τ. Searches for massive charged leptons are given elsewhere, and searches for the mixing of $(\mu^- e^+)$ and $(\mu^+ e^-)$ are given in the muon Listings.

Discussion of the current neutrino mass limits and the theory of mixing are given in the note on "Neutrino Mass" by Boris Kayser just before the ν_e Listings.

In many of the following Listings (*e.g.* neutrino disappearance and appearance experiments), results are presented assuming that mixing occurs only between two neutrino species, such as $\nu_\tau \leftrightarrow \nu_e$. This assumption is also made for lepton-number violating mixing between two states, such as $\nu_e \leftrightarrow \overline{\nu}_\mu$ or $\nu_\mu \leftrightarrow \overline{\nu}_\mu$. As discussed in Kayser's review, the assumption of mixing between only two states is valid if (a) all mixing angles are small or (b) there is a mass hierarchy such that one ΔM^2_{ij}, *e.g.* $\Delta M^2_{21} = M^2_{\nu_2} - M^2_{\nu_1}$, is small compared with the others, so that there is a region in L/E (the ratio of the distance L that the neutrino travels to its energy E) where $\Delta M^2_{21} L/E$ is negligible, but $\Delta M^2_{32} L/E$ is not.

In this case limits or results can be shown as allowed regions on a plot of $|\Delta M^2|$ as a function of $\sin^2 2\theta$. The simplest situation occurs in an "appearance" experiment, where one searches for interactions by neutrinos of a variety not expected in the beam. An example is the search for ν_e interactions in a detector in a ν_μ beam. For oscillation between two states, the probability that the "wrong" state will appear is given by Eq. 11 in Kayser's review, which may be written as

$$P = \sin^2 2\theta \, \sin^2(1.27 \Delta M^2 L/E) \, , \qquad (1)$$

where $|\Delta M^2|$ is in eV^2 and L/E is in km/GeV or m/MeV. In a real experiment L and E have some spread, so that one must average P over the distribution of L/E. As an example, let us make the somewhat unrealistic assumption that $b \equiv 1.27 L/E$ has a Gaussian distribution with standard deviation σ_b about a central value b_0. Then:

$$\langle P \rangle = \tfrac{1}{2} \sin^2 2\theta [1 - \cos(2 b_0 \Delta M^2) \exp(-2\sigma_b^2 (\Delta M^2)^2)] \qquad (2)$$

The value of $\langle P \rangle$ is set by the experiment. For example, if 230 interactions of the expected flavor are detected and none of the wrong flavor are seen, then $P = 0.010$ at the 90% CL. * A superior statistical analysis of confidence limits in the $\sin^2 2\theta$-$|\Delta M^2|$ plane is given in Ref. 1. We can then solve the above expression for $\sin^2 2\theta$ as a function of $|\Delta M^2|$. This function is shown in Fig. 1. † Curve generated with $\langle P \rangle = 0.005$, $\langle L/E \rangle = 1.11$, and $\sigma_b / b_0 = 0.08$. Note that:

(a) since the fast oscillations are completely washed out by the resolution for large $|\Delta M^2|$, $\sin^2 2\theta = 2 \langle P \rangle$ in this region;
(b) the maximum excursion of the curve to the left is to $\sin^2 2\theta = \langle P \rangle$ with good resolution, with smaller excursion for worse resolution. This "bump" occurs at $|\Delta M^2| = \pi / 2 b_0$ eV^2;
(c) for large $\sin^2 2\theta$, $\Delta M^2 \approx (\langle P \rangle / \sin^2 2\theta)^{1/2} / b_0$; and, consequently,
(d) the intercept at $\sin^2 2\theta = 1$ is at $\Delta M^2 = \sqrt{\langle P \rangle} / b_0$.

The intercept for large $|\Delta M^2|$ is a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ depends also on the mean value of L/E. The wiggles depend on experimental features such as the size of the source, the neutrino energy distribution, and detector and analysis features. Aside from such details, the two intercepts completely describe the exclusion region: For large $|\Delta M^2|$, $\sin^2 2\theta$ is constant and equal to $2 \langle P \rangle$, and for large $\sin^2 2\theta$ the slope is known from the intercept. For these reasons, it is (nearly) sufficient to summarize the results of an experiment by stating the two intercepts, as is done in the following tables. The reader is referred to the original papers for the two-dimensional plots expressing the actual limits.

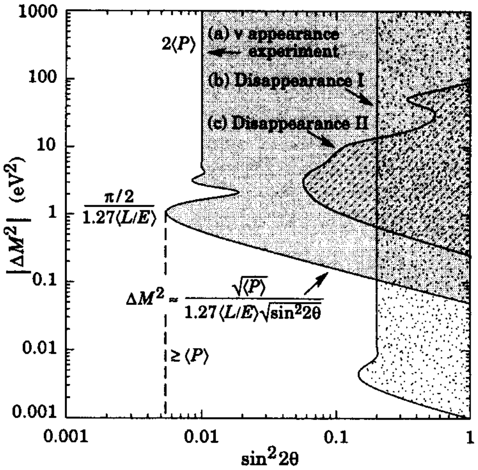

Figure 1: Neutrino oscillation parameter ranges excluded by two hypothetical experiments (a and b) described by Eq. (2) and one real one (c). Parameters for the first two cases are given in the footnotes. In case (a) one searches for the appearance of neutrinos not expected in the beam. The probability of appearance, in this case 0.5% at some specified CL, is set by the number of right-flavor events observed and/or information about the flux and cross sections. Case (b) represents a disappearance experiment in which the flux is known in the absence of mixing. In case (c), the information comes from measured fluxes at two distances from the target [4].

If a positive effect is claimed, then the excluded region is replaced by an allowed band or allowed regions. This is the case for the LSND experiment [2] and the SuperKamiokande analysis of R(μ/e) for atmospheric neutrinos [3].

In a "disappearance" experiment, one looks for the attenuation of the beam neutrinos (for example, ν_k) by mixing with at least one other neutrino eigenstate. (We label such experiments as $\nu_k \not\rightarrow \nu_k$.) The probability that a neutrino remains the same neutrino from the production point to detector is given by

$$P(\nu_k \rightarrow \nu_k) = 1 - P(\nu_k \rightarrow \nu_j) \ , \qquad (3)$$

where mixing occurs between the kth and jth species with $P(\nu_k \rightarrow \nu_j)$ given by Eq. (1) or Eq. (2).

In contrast to the detection of even a few "wrong-flavor" neutrinos establishing mixing in an appearance experiment, the disappearance of a few "right-flavor" neutrinos in a disappearance experiment goes unobserved because of statistical fluctuations. For this reason, disappearance experiments usually cannot establish small-probability (small $\sin^2 2\theta$) mixing.

Disappearance experiments fall into two general classes:

I. Those in which the beam neutrino flux is known, from theory or from other measurements. Examples are reactor $\overline{\nu}_e$ experiments and certain accelerator experiments. Although such experiments cannot establish very small-$\sin^2 2\theta$ mixing, they can establish small limits on ΔM^2 for large $\sin^2 2\theta$ because L/E can be very large. An example, based on the Chooz reactor measurements [5], is labeled "Disappearance I" in Fig. 1. [‡]Curve parameters $\langle P\rangle = 0.1$, $\langle L/E\rangle = 237$, and $\sigma_b/b_0 = 0.5$. For the actual Chooz experiment [5], $\langle L/E\rangle \approx 300$ and the limit on $\langle P\rangle$ is 0.09.

II. Those in which attenuation or oscillation of the beam neutrino flux is measured in the apparatus itself (two detectors, or a "long" detector). Above some minimum $|\Delta M^2|$ the equilibrium is established upstream, and there is no change in intensity over the length of the apparatus. As a result, sensitivity is lost at high $|\Delta M^2|$, as can be seen by the curve labeled "Disappearance II" in Fig. 1 [4]. Such experiments have not been competititive for a long time. However, a new generation of long-baseline experiments with a "near" detector and a "far" detector with very large L, *e.g.*, MINOS, will be able to use this strategy to advantage.

Finally, there are more complicated cases, such as analyses of solar neutrino data in terms of the MSW parameters [6]. For a variety of physical reasons, an irregular region in the $|\Delta M^2|$ vs $\sin^2 2\theta$ plane is allowed. It is difficult to represent these graphical data adequately within the strictures of our tables.

References

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(A) Heavy neutral leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m < 2400$ GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \rightarrow \nu\gamma$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>69.8	95	[2] ACKERSTAFF	98C	OPAL	Majorana, coupling to e
>79.1	95	[2] ACKERSTAFF	98C	OPAL	Dirac, coupling to e
>68.7	95	[2] ACKERSTAFF	98C	OPAL	Majorana, coupling to μ
>78.5	95	[2] ACKERSTAFF	98C	OPAL	Dirac, coupling to μ

>54.4	95	[2] ACKERSTAFF 98C	OPAL	Majorana, coupling to τ
>69.0	95	[2] ACKERSTAFF 98C	OPAL	Dirac, coupling to τ
>78.0	95	[2] ACCIARRI 97P	L3	Dirac coupling to e
>66.7	95	[2] ACCIARRI 97P	L3	Majorana coupling to e
>78.0	95	[2] ACCIARRI 97P	L3	Dirac coupling to μ
>66.7	95	[2] ACCIARRI 97P	L3	Majorana coupling to μ
>72.2	95	[2] ACCIARRI 97P	L3	Dirac coupling to τ
>58.2	95	[2] ACCIARRI 97P	L3	Majorana coupling to τ
>63	95	[3,4] BUSKULIC 96S	ALEP	Dirac
>54.3	95	[3,5] BUSKULIC 96S	ALEP	Majorana

• • • We do not use the following data for averages, fits, limits, etc. • • •

>59.3	95	ACCIARRI 96G	L3	Dirac coupling to e
>57.9	95	ACCIARRI 96G	L3	Dirac coupling to μ
>48.6	95	ACCIARRI 96G	L3	Majorana coupling to e
>47.2	95	ACCIARRI 96G	L3	Majorana coupling to μ
>62.5	95	ALEXANDER 96P	OPAL	Dirac coupling to e
>63.0	95	ALEXANDER 96P	OPAL	Dirac coupling to μ
>57.4	95	ALEXANDER 96P	OPAL	Dirac coupling to τ
>51.4	95	ALEXANDER 96P	OPAL	Majorana coupling to e
>52.2	95	ALEXANDER 96P	OPAL	Majorana coupling to μ
>44.2	95	ALEXANDER 96P	OPAL	Majorana coupling to τ
>44.5	95	[6] ABREU 92B	DLPH	Dirac
>39.0	95	[6] ABREU 92B	DLPH	Majorana
none 2.5–50	95	[7] ADRIANI 92I	L3	$\lvert U_{\tau\text{ or }\mu}\rvert^2 < 3\times10^{-4}$
none 4–50	95	[7] ADRIANI 92I	L3	$\lvert U_{\tau}\rvert^2 < 3\times10^{-4}$
>46.4	95	[8] ADEVA 90S	L3	Dirac
>45.1	95	[8] ADEVA 90S	L3	Majorana
>46.5	95	[9] AKRAWY 90L	OPAL	Coupling to e or μ
>45.7	95	[9] AKRAWY 90L	OPAL	Coupling to τ
>41	95	[10,11] BURCHAT 90	MRK2	Dirac, $\lvert U_{\ell J}\rvert^2 > 10^{-10}$
>19.6	95	[10,11] BURCHAT 90	MRK2	Dirac, all $\lvert U_{\ell J}\rvert^2$
none 25–45.7	95	[10,12] DECAMP 90F	ALEP	Dirac $\lvert U_{\ell J}\rvert^2 > 10^{-13}$
none 8.2–26.5	95	[13] SHAW 89	AMY	Dirac L^0, $\lvert U_{eJ}\rvert^2 > 10^{-6}$
none 8.3–22.4	95	[13] SHAW 89	AMY	Majorana L^0, $\lvert U_{eJ}\rvert^2 > 10^{-6}$
none 8.1–24.9	95	[13] SHAW 89	AMY	Majorana L^0, $\lvert U_{\mu J}\rvert^2 > 10^{-6}$
none 1.8–6.7	90	[14] AKERLOF 88	HRS	$\lvert U_{eJ}\rvert^2$=1
none 1.8–6.4	90	[14] AKERLOF 88	HRS	$\lvert U_{\mu J}\rvert^2$=1
none 2.5–6.3	80	[14] AKERLOF 88	HRS	$\lvert U_{\tau J}\rvert^2$=1
none 0.25–14	90	[15] MISHRA 87	CNTR	$\lvert U_{\mu J}\rvert^2$=1.
none 0.25–10	90	[15] MISHRA 87	CNTR	$\lvert U_{\mu J}\rvert^2$=0.1
none 0.25–7.7	90	[15] MISHRA 87	CNTR	$\lvert U_{\mu J}\rvert^2$=0.03
none 1.–2.	90	[16] WENDT 87	MRK2	$\lvert U_{e\text{ or }\mu J}\rvert^2$=0.1
none 2.2–4.	90	[16] WENDT 87	MRK2	$\lvert U_{e\text{ or }\mu J}\rvert^2$=0.001
none 2.3–3.	90	[16] WENDT 87	MRK2	$\lvert U_{\tau J}\rvert^2$=0.1
none 3.2–4.8	90	[16] WENDT 87	MRK2	$\lvert U_{\tau J}\rvert^2$=0.001
none 0.3–0.9	90	[17] BADIER 86	CNTR	$\lvert U_{eJ}\rvert^2$=0.8
none 0.33–2.0	90	[17] BADIER 86	CNTR	$\lvert U_{eJ}\rvert^2$=0.03
none 0.6–0.7	90	[17] BADIER 86	CNTR	$\lvert U_{\mu J}\rvert^2$=0.8
none 0.6–2.0	90	[17] BADIER 86	CNTR	$\lvert U_{\mu J}\rvert^2$=0.01–0.001
> 1.2		MEYER 77	MRK1	Neutral

[2] The decay length of the heavy lepton is assumed to be < 1 cm, limiting the square of the mixing angle $\lvert U_{\ell J}\rvert^2$ to 10^{-12}.

[3] BUSKULIC 96S requires the decay length of the heavy lepton to be < 1 cm, limiting the square of the mixing angle $\lvert U_{\ell J}\rvert^2$ to 10^{-10}.

[4] BUSKULIC 96S limit for mixing with τ. Mass is > 63.6 GeV for mixing with e or μ.

[5] BUSKULIC 96S limit for mixing with τ. Mass is > 55.2 GeV for mixing with e or μ.

[6] ABREU 92B limit is for mixing matrix element ≈ 1 for coupling to e or μ. Reduced somewhat for coupling to τ, increased somewhat for smaller mixing matrix element. Replaces ABREU 91F.

[7] ADRIANI 92I is a search for isosinglet heavy lepton N_ℓ which might be produced from $Z \rightarrow \nu_\ell N_\ell$, then decay via a number of different channels. Limits are weaker for decay lengths longer than about 1 m.

[8] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $\lvert U_{1J}\rvert^2 + \lvert U_{2J}\rvert^2 + \lvert U_{3J}\rvert^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

[9] AKRAWY 90L limits valid if coupling strength is greater than a mass-dependent value, e.g., 4.9×10^{-7} at $m_{L^0} = 20$ GeV, 3.5×10^{-8} at 30 GeV, 4×10^{-9} at 40 GeV.

[10] Limits apply for $\ell = e$, μ, or τ and for $V-A$ decays of Dirac neutrinos.

[11] BURCHAT 90 searched for Z decay to unstable L^0 pairs at SLC. It includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[12] For $25 < m_{L^0} < 42.7$ GeV, DECAMP 90F exclude an L^0 for all values of $\lvert U_{\ell J}\rvert^2$.

[13] SHAW 89 also excludes the mass region from 8.0 to 27.2 GeV for Dirac L^0 and from 8.1 to 23.6 GeV for Majorana L^0 with equal full-strength couplings to e and μ. SHAW 89 also gives correlated bounds on lepton mixing.

[14] AKERLOF 88 is PEP e^+e^- experiment at $E_{\rm cm} = 29$ GeV. The L^0 is assumed to decay via $V-A$ to e or μ or τ plus a virtual W.

[15] MISHRA 87 is Fermilab neutrino experiment looking for either dimuon or double vertex events (hence long-lived).

[16] WENDT 87 is MARK-II search at PEP for heavy ν with decay length 1–20 cm (hence long-lived).

[17] BADIER 86 is a search for a long-lived penetrating sequential lepton produced in π^- – nucleon collisions with lifetimes in the range from 5×10^{-7} – 5×10^{-11} s and decaying into at least two charged particles. U_{eJ} and U_{mJ} are mixing angles to ν_e and ν_μ. See also the BADIER 86 entry in the section "Searches for Massive Neutrinos and Lepton Mixing".

Astrophysical Limits on Neutrino MASS for m_ν > 1 GeV

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 60–115		[18] FARGION 95	ASTR	Dirac
none 9.2–2000		[19] GARCIA 95	COSM	Nucleosynthesis
none 26–4700		[19] BECK 94	COSM	Dirac
none 6 – hundreds		[20,21] MORI 92B	KAM2	Dirac neutrino
none 24 – hundreds		[20,21] MORI 92B	KAM2	Majorana neutrino
none 10–2400	90	[22] REUSSER 91	CNTR	HPGe search
none 3–100	90	SATO 91	KAM2	Kamiokande II
		[23] ENQVIST 89	COSM	
none 12–1400		[19] CALDWELL 88	COSM	Dirac ν
none 4–16	90	[19,20] OLIVE 88	COSM	Dirac ν
none 4–35	90	OLIVE 88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI 88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI 88	COSM	Majorana ν
none 20–1000	95	[19] AHLEN 87	COSM	Dirac ν
>4.1		GRIEST 87	COSM	Dirac ν

[18] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.

[19] These results assume that neutrinos make up dark matter in the galactic halo.

[20] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[21] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[22] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[23] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Sum of neutrino masses

Revised April 1998 by K.A. Olive (University of Minnesota).

The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu = m_{\rm tot}(3/11) n_\gamma ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 412$ cm^{-3}, we have

$$\Omega_\nu h^2 = m_{\rm tot}/(94 \text{ eV}) .$$

Therefore, a limit on $\Omega_\nu h^2$ such as $\Omega_\nu h^2 < 0.25$ gives the limit

$$m_{\rm tot} < 24 \text{ eV} .$$

The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
<180	SZALAY 74	COSM
<132	COWSIK 72	COSM
<280	MARX 72	COSM
<400	GERSHTEIN 66	COSM

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<100–200	[24] OLIVE 82	COSM	Dirac ν
<200–2000	[24] OLIVE 82	COSM	Majorana ν

[24] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
> 10	[25] OLIVE 82	COSM	G_R/G_F <0.1
>100	[25] OLIVE 82	COSM	G_R/G_F <0.01

[25] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >1.2 GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

(C) Searches for neutrinoless double-β decay

LIMITS FROM NEUTRINOLESS ββ DECAY

Revised 1995 by P. Vogel (Caltech).

Limits on an effective Majorana neutrino mass and a lepton-number violating current admixture can be obtained from lifetime limits on $0\nu\beta\beta$ nuclear decay. The derived quantities are model-dependent, so the half-life measurements are given first. Where possible we list the references for the matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei. For further calculations, see, *e.g.*, Ref. 1

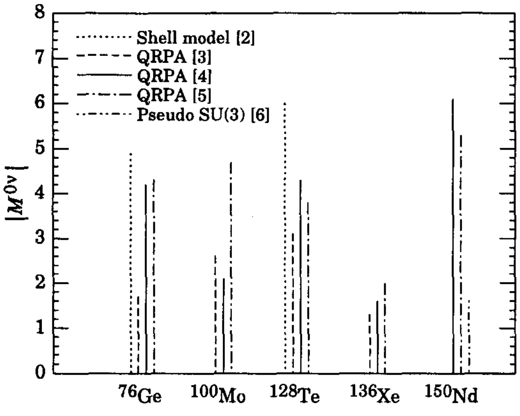

Figure 1: Nuclear matrix elements for $0\nu\beta\beta$ decay calculated by a subset of different methods and different authors for the most popular double-beta decay candidate nuclei. Recalculated from the published half-lives using consistent phase-space factors and $g_A = 1.25$. The QRPA [3] value is for $\alpha' = -390$ MeV fm^3.

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$H_W = (G_F/\sqrt{2})$$
$$\times (J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.}$$

where $j_L^\mu = \bar{e}_L \gamma^\mu \nu_{eL}$, $j_R^\mu = \bar{e}_R \gamma^\mu \nu_{eR}$, and J_L^μ and J_R^μ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to κ, but quote limits on quantities proportional to η and λ.* In analogy to $\langle m_\nu \rangle$ (see Eq. 11 in the "Note on Neutrinos" at the beginning of the Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$ and $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$, where V_{ij} is a matrix analogous to U_{ij} (see Eq. 2 in the "Note on Neutrinos"), but describing the mixing among right-handed neutrinos. The quantities $\langle \eta \rangle$ and $\langle \lambda \rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu \rangle$, cancellations are possible in $\langle \eta \rangle$ and $\langle \lambda \rangle$. The limits on $\langle \eta \rangle$ are of order 10^{-8} while the limits on $\langle \lambda \rangle$ are of order 10^{-6}. The reader is warned that a number of earlier experiments did not distinguish between η and λ. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

Footnotes and References

* We have previously used a less accepted but more explicit notation in which $\eta_{RL} \equiv \kappa$, $\eta_{LR} \equiv \eta$, and $\eta_{RR} \equiv \lambda$.

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3. J. Engel, P. Vogel, and M.R. Zirnbauer, Phys. Rev. **C37**, 731 (1988).
4. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
5. T. Tomoda, Rept. on Prog. in Phys. **54**, 53, (1991).
6. J.G. Hirsch, O. Castaños, and P.O. Hess, Nucl. Phys. **A582**, 124 (1995).

Half-life Measurements and Limits for Double β Decay

In all cases of double beta decay, (Z,A) → (Z+2,A) + $2\beta^-$ + (0 or 2)$\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE	TRANSITION		METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$(7.6^{+2.2}_{-1.4})$E18		^{100}Mo	2ν		Si(Li)	[26] ALSTON-...	97
> 0.19	90	^{92}Mo	$0\nu+2\nu$	$0^+ \to 0^+$	γ in HPGe	[27] BARABASH	97
> 0.81	90	^{92}Mo	$0\nu+2\nu$	$0^+ \to 0_1^+$	γ in HPGe	[27] BARABASH	97
> 0.89	90	^{92}Mo	$0\nu+2\nu$	$0^+ \to 2_1^+$	γ in HPGe	[27] BARABASH	97
>11000	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	[28] BAUDIS	97
$(6.82^{+0.38}_{-0.53} \pm 0.68)$E18		^{100}Mo	2ν		TPC	[29] DESILVA	97
$(6.75^{+0.37}_{-0.42} \pm 0.68)$E18		^{150}Nd	2ν		TPC	[30] DESILVA	97
> 1.2	90	^{150}Nd	0ν		TPC	[31] DESILVA	97
$1.77 \pm 0.01^{+0.13}_{-0.11}$		^{76}Ge	2ν		Enriched HPGe	[32] GUENTHER	97
> 32.5	90	^{130}Te	0ν		Bolometer	[33] ALESSAND...	96B
$(3.75 \pm 0.35 \pm 0.21)$E19		^{116}Cd	2ν	$0^+ \to 0^+$	NEMO 2	[34] ARNOLD	96
$0.043^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν		TPC	[35] BALYSH	96
> 52	68	^{100}Mo	$0\nu,\langle m_\nu \rangle$	$0^+ \to 0^+$	ELEGANT V	[36] EJIRI	96
> 39	68	^{100}Mo	$0\nu,\langle \lambda \rangle$	$0^+ \to 0^+$	ELEGANT V	[36] EJIRI	96

> 51	68	^{100}Mo	$0\nu,\langle\eta\rangle$	$0^+ \to 0^+$	ELEGANT V	[36] EJIRI	96
0.79 ± 0.10		^{130}Te	$0\nu{+}2\nu$		Geochem	[37] TAKAOKA	96
$0.61^{+0.18}_{-0.11}$		^{100}Mo	$0\nu{+}2\nu$	$0^+ \to 0^+_1$	γ in HPGe	[38] BARABASH	95
> 0.00013	99	^{160}Gd	2ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[39] BURACHAS	95
> 0.00012	99	^{160}Gd	2ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[39] BURACHAS	95
> 0.014	90	^{160}Gd	0ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[39] BURACHAS	95
> 0.013	90	^{160}Gd	0ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[39] BURACHAS	95
$(9.5 \pm 0.4 \pm 0.9)$E18		^{100}Mo	2ν		NEMO 2	DASSIE	95
> 0.6	90	^{100}Mo	0ν	$0^+ \to 0^+_1$	NEMO 2	DASSIE	95
$0.026^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \to 0^+$	ELEGANT IV	EJIRI	95
> 29	90	^{116}Cd	0ν	$0^+ \to 0^+$	$^{116}CdWO_4$ scint	[40] GEORGADZE	95
> 0.3	68	^{160}Gd	0ν		Gd_2SiO_5: Ce scint	KOBAYASHI	95
> 2.37	90	^{116}Cd	$0\nu{+}2\nu$	$0^+ \to 2^+$	γ in HPGe	[41] PIEPKE	94
> 2.05	90	^{116}Cd	$0\nu{+}2\nu$	$0^+ \to 0^+_1$	γ in HPGe	[41] PIEPKE	94
> 2.05	90	^{116}Cd	$0\nu{+}2\nu$	$0^+ \to 0^+_2$	γ in HPGe	[41] PIEPKE	94
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \to 0^+$	TPC	ARTEMEV	93
0.039 ± 0.009		^{96}Mo	$0\nu{+}2\nu$		Geochem	KAWASHIMA	93
> 340	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[42] VUILLEUMIER	93
> 260	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[43] VUILLEUMIER	93
> 0.21	90	^{136}Xe	2ν	$0^+ \to 0^+$	TPC	VUILLEUMIER	93
> 430	90	^{76}Ge	0ν	$0^+ \to 2^+$	Enriched HPGe	BALYSH	92
2.7 ± 0.1		^{130}Te			Geochem	BERNATOW...	92
7200 ± 400		^{128}Te			Geochem	[44] BERNATOW...	92
> 27	68	^{82}Se	0ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
$0.92^{+0.07}_{-0.04}$		^{76}Ge	2ν	$0^+ \to 0^+$	Enriched HPGe	[45] AVIGNONE	91
> 3.3	95	^{136}Xe	0ν	$0^+ \to 2^+$	Prop cntr	[46] BELLOTTI	91
> 0.16	95	^{136}Xe	2ν		Prop cntr	BELLOTTI	91
2.0 ± 0.6		^{238}U			Radiochem	[47] TURKEVICH	91
> 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
$1.12^{+0.48}_{-0.26}$		^{76}Ge	2ν	$0^+ \to 0^+$	HPGe	[48] MILEY	90
0.9 ± 0.1		^{76}Ge	2ν		Enriched Ge(Li)	VASENKO	90
> 4.7	68	^{128}Te		$0^+ \to 2^+$	Ge(Li)	[39] BELLOTTI	87
> 4.5	68	^{130}Te		$0^+ \to 2^+$	Ge(Li)	[39] BELLOTTI	87
> 800	95	^{128}Te			Geochem	[49] KIRSTEN	83
2.60 ± 0.28		^{130}Te			Geochem	[49] KIRSTEN	83

[26] ALSTON-GARNJOST 97 report evidence for 2ν decay of ^{100}Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[27] BARABASH 97 measure limits for β^+, EC, and ECEC decay of ^{92}Mo to the ground and excited states of ^{92}Ru, respectively. Limits are not competive compared to $\beta^-\beta^-$ searches as far as sensitivity to $\langle m_\nu\rangle$ or RHC admixtures is concerned.

[28] BAUDIS 97 limit for 0ν decay of enriched ^{76}Ge using Ge calorimeters supersedes GUENTHER 97.

[29] DESILVA 97 result for 2ν decay of ^{100}Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[30] DESILVA 97 result for 2ν decay of ^{150}Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[31] DESILVA 97 do not explain whether their efficiency for 0ν decay of ^{150}Nd was calculated under the assumption of a $\langle m_\nu\rangle$, $\langle\lambda\rangle$, or $\langle\eta\rangle$ driven decay.

[32] GUENTHER 97 half-life for the 2ν decay of ^{76}Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

[33] ALESSANDRELLO 96B experiment can distinguish the 0ν and 2ν modes; it shows that the geochemical observation of ^{130}Te decay (BERNATOWICZ 92, KIRSTEN 83, TAKAOKA 96) is dominanted by the 2ν decay. Supersedes ALESSANDRELLO 94.

[34] ARNOLD 96 measure the 2ν decay of ^{116}Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[35] BALYSH 96 measure the 2ν decay of ^{48}Ca, using a passive source of enriched ^{48}Ca in a TPC.

[36] EJIRI 96 use energy and angular correlations of the 2β-rays in efficiency estimate to give limits for the 0ν decay modes associated with $\langle m_\nu\rangle$, $\langle\lambda\rangle$, and $\langle\eta\rangle$, respectively. Enriched ^{100}Mo source is used in tracking calorimeter. These are the best limits for ^{100}Mo. Limit is more stringent than ALSTON-GARNJOST 97.

[37] TAKAOKA 96 measure the geochemical half-life of ^{130}Te. Their value is in disagreemnt with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[38] BARABASH 95 cannot distinguish 0ν and 2ν, but it is inferred indirectly that the 0ν mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[39] BELLOTTI 87 searches for γ rays for 2^+ state decays in corresponding Xe isotopes. Limit for ^{130}Te case argues for dominant $0^+ \to 0^+$ transition in known decay of this isotope.

[40] GEORGADZE 95 result for this and other modes are also give in DANEVICH 95. Result for 2ν decay omitted because of authors' caveats.

[41] In PIEPKE 94, the studied excited states of ^{116}Sn have energies above the ground state of 1.2935 MeV for the 2^+ state, 1.7568 MeV for the 0^+_1 state, and 2.0273 for the 0^+_2 state.

[42] Limit in the case of a transition induced by a Majorana mass.

[43] Limit for lepton-number violating right-handed current-induced (RHC) decay.

[44] BERNATOWICZ 92 finds ^{128}Te/^{130}Te activity ratio from slope of ^{128}Xe/^{132}Xe vs ^{130}Xe/^{132}Xe ratios during extraction, and normalizes to lead-dated ages for the ^{130}Te lifetime. The authors state that their results imply that "(a) the double beta decay of ^{128}Te has been firmly established and its half-life has been determined ... without any ambiguity due to trapped Xe interferences... (b) Theoretical calculations ... underestimate the [long half-lives of ^{128}Te ^{130}Te] by 1 or 2 orders of magnitude, pointing to a real supression in the 2ν decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of 2ν decay widths ... in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray ^{128}Xe production corrections.

[45] AVIGNONE 91 reports confirmation of the MILEY 90 and VASENKO 90 observations of $2\nu\beta\beta$ decay of ^{76}Ge. Error is 2σ.

[46] BELLOTTI 91 uses difference between natural and enriched ^{136}Xe runs to obtain $\beta\beta0\nu$ limits, leading to "less stringent, but safer limits."

[47] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[48] MILEY 90 claims only "suggestive evidence" for the decay. Error is 2σ.

[49] KIRSTEN 83 reports "2σ" error. References are given to earlier determinations of the ^{130}Te lifetime.

$\langle m_\nu\rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double β Decay

$\langle m_\nu\rangle = |\Sigma\ U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{1j}, not $|U_{1j}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

VALUE (eV)	*CL%*	*ISOTOPE*		*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<9.3	68	^{100}Mo	0ν		Si(Li)	[50] ALSTON-...	97
<0.46	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	[51] BAUDIS	97
<2.2	68	^{100}Mo	0ν	$0^+ \to 0^+$	ELEGANT V	[52] EJIRI	96
<4.1	90	^{116}Cd	0ν		$^{116}CdWO_4$ scint	[53] DANEVICH	95
< 2.8–4.3	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[54] VUILLEUMIER	93
< 1.1–1.5		^{128}Te			Geochem	[55] BERNATOW...	92
<5	68	^{82}Se			TPC	[56] ELLIOTT	92
<8.3	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
<5.6	95	^{128}Te			Geochem	KIRSTEN	83

[50] ALSTON-GARNJOST 97 obtain the limit for $\langle m_\nu\rangle$ using the matrix elements of ENGEL 88. The limit supersedes ALSTON-GARNJOST 93.

[51] BAUDIS 97 limit for $\langle m_\nu\rangle$ is based on the matrix elements of STAUDT 90. This is the most stringent bound on $\langle m_\nu\rangle$. It supersedes the limit of GUENTHER 97.

[52] EJIRI 96 obtain the limit for $\langle m_\nu\rangle$ using the matrix elements of TOMODA 91.

[53] DANEVICH 95 is identical to GEORGADZE 95.

[54] VUILLEUMIER 93 mass range from parameter range in the Caltech calculations (ENGEL 88). On the basis of these calculations, the BALYSH 92 mass range would be < 2.2–4.4 eV.

[55] BERNATOWICZ 92 finds these majoron mass limits assuming that the measured geochemical decay width is a limit on the 0ν decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

[56] ELLIOTT 92 uses the matrix elements of HAXTON 84.

Limits on Lepton-Number Violating ($V{+}A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle\lambda\rangle = \lambda\sum U_{1j}V_{1j}$ and $\langle\eta\rangle = \eta\sum U_{1j}V_{1j}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$\langle\lambda\rangle$ (10^{-6})	*CL%*	*$\langle\eta\rangle$ (10^{-8})*	*CL%*	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	[57] GUENTHER	97
<3.7	68	<2.5	68	^{100}Mo	Elegant V	[58] EJIRI	96
<5.3	90	<5.9	90	^{116}Cd	$^{116}CdWO_4$ scint	[59] DANEVICH	95
<4.4	90	<2.3	90	^{136}Xe	TPC	[60] VUILLEUMIER	93
		<5.3		^{128}Te	Geochem	[61] BERNATOW...	92

[57] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.

[58] EJIRI 96 obtain limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ using the matrix elements of TOMODA 91.

[59] DANEVICH 95 is identical to GEORGADZE 95.

[60] VUILLEUMIER 93 uses the matrix elements of MUTO 89.

[61] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η. Further details of the experiment are given in BERNATOWICZ 93.

(D) Other bounds from nuclear and particle decays

Limits on $|U_{1j}|^2$ as Function of m_{ν_j}

Peak and kink search tests

Limits on $|U_{1j}|^2$ as function of m_{ν_j}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1 × 10^{-7}	90	[62] BRITTON	92B	CNTR	50 MeV < m_{ν_j} < 130 MeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<5 \times 10^{-6}$	90	DELEENER-...	91		$m_{\nu_j} = 20$ MeV
$<5 \times 10^{-7}$	90	DELEENER-...	91		$m_{\nu_j} = 40$ MeV
$<3 \times 10^{-7}$	90	DELEENER-...	91		$m_{\nu_j} = 60$ MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		$m_{\nu_j} = 80$ MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		$m_{\nu_j} = 100$ MeV
$<5 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_j}=60 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_j}=80 MeV
$<3 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_j}=100 MeV
$<1 \times 10^{-6}$	90	AZUELOS	86	CNTR	m_{ν_j}=120 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_j}=130 MeV
$<8 \times 10^{-6}$		DELEENER-...	86	CNTR	m_{ν_j}=20 MeV
$<4 \times 10^{-7}$		DELEENER-...	86	CNTR	m_{ν_j}=60 MeV
$<2 \times 10^{-6}$		DELEENER-...	86	CNTR	m_{ν_j}=100 MeV
$<7 \times 10^{-6}$		DELEENER-...	86	CNTR	m_{ν_j}=120 MeV
$<1 \times 10^{-4}$	90	[63] BRYMAN	83B	CNTR	m_{ν_j}=5 MeV
$<1.5 \times 10^{-6}$	90	BRYMAN	83B	CNTR	m_{ν_j}=53 MeV
$<1 \times 10^{-5}$	90	BRYMAN	83B	CNTR	m_{ν_j}=70 MeV
$<1 \times 10^{-4}$	90	BRYMAN	83B	CNTR	m_{ν_j}=130 MeV
$<1 \times 10^{-4}$	68	[64] SHROCK	81	THEO	m_{ν_j}=10 MeV
$<5 \times 10^{-6}$	68	[64] SHROCK	81	THEO	m_{ν_j}=60 MeV
$<1 \times 10^{-5}$	68	[65] SHROCK	80	THEO	m_{ν_j}=80 MeV
$<3 \times 10^{-6}$	68	[65] SHROCK	80	THEO	m_{ν_j}=160 MeV

[62] BRITTON 92B is from a search for additional peaks in the e^+ spectrum from $\pi^+ \rightarrow e^+ \nu_e$ decay at TRIUMF. See also BRITTON 92.

[63] BRYMAN 83B obtain upper limits from both direct peak search and analysis of $B(\pi \rightarrow e\nu)/B(\pi \rightarrow \mu\nu)$. Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).

[64] Analysis of $(\pi^+ \rightarrow e^+ \nu_e)/(\pi^+ \rightarrow \mu^+ \nu_\mu)$ and $(K^+ \rightarrow e^+ \nu_e)/(K^+ \rightarrow \mu^+ \nu_\mu)$ decay ratios.

[65] Analysis of $(K^+ \rightarrow e^+ \nu_e)$ spectrum.

Kink search in nuclear β decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)). Limits on $|U_{1j}|^2$ as a function of m_{ν_j}. See WIETFELDT 96 for a comprehensive review.

VALUE (units 10^{-3})	*CL%*	m_{ν_j} (keV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1 \times 10^{-2}$	95	1	^{3}H	SPEC	[66] HIDDEMANN	95
$< 6 \times 10^{-3}$	95	2	^{3}H	SPEC	[66] HIDDEMANN	95
$< 2 \times 10^{-3}$	95	3	^{3}H	SPEC	[66] HIDDEMANN	95
$< 2 \times 10^{-3}$	95	4	^{3}H	SPEC	[66] HIDDEMANN	95
$0.3 \pm 1.5 \pm 0.8$		17	^{35}S	Mag spect	[67] BERMAN	93
< 2.8	99	17	^{3}H	Prop chamber	[68] KALBFLEISCH	93
< 1	99	14.4–15.2	^{3}H	Prop chamber	[68] KALBFLEISCH	93
< 0.7	99	16.3–16.6	^{3}H	Prop chamber	[68] KALBFLEISCH	93
< 2	95	13–40	^{35}S	Si(Li)	[69] MORTARA	93
< 0.73	95	17	^{63}Ni	Mag spect	OHSHIMA	93
< 1.5	95	10.5–25.0	^{63}Ni	Mag spect	[70] OHSHIMA	93
< 6	95	5–25	^{55}Fe	IBEC in Ge	[71] WIETFELDT	93
< 2	90	17	^{35}S	Mag spect.	[72] CHEN	92
< 0.95	95	17	^{63}Ni	Mag spect	[73] KAWAKAMI	92
< 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI	92
< 10	90	16–35	^{125}I	IBEC; γ det	[74] BORGE	86
< 7.5	99	5–50	^{35}S	Mag spect	ALTZITZOG...	85
< 8	90	80	^{35}S	Mag spect	[75] APALIKOV	85
< 1.5	90	60	^{35}S	Mag spect	APALIKOV	85
< 8	90	30	^{35}S	Mag spect	APALIKOV	85
< 3	90	17	^{35}S	Mag spect	APALIKOV	85
< 45	90	4	^{35}S	Mag spect	APALIKOV	85
< 10	90	5–30	^{35}S	Si(Li)	DATAR	85
< 3.0	90	5–50		Mag spect	MARKEY	85
< 0.62	90	48	^{35}S	Si(Li)	OHI	85
< 0.90	90	30	^{35}S	Si(Li)	OHI	85
< 1.30	90	20	^{35}S	Si(Li)	OHI	85
< 1.50	90	17	^{35}S	Si(Li)	OHI	85
< 3.30	90	10	^{35}S	Si(Li)	OHI	85
< 25	90	30	^{64}Cu	Mag spect	[76] SCHRECK...	83
< 4	90	140	^{64}Cu	Mag spect	[76] SCHRECK...	83
< 8	90	440	^{64}Cu	Mag spect	[76] SCHRECK...	83
< 1	95	0.1			[77] SIMPSON	81B
<4E−3	95	10			[77] SIMPSON	81B
<100	90	0.1–3000		THEO	[78] SHROCK	80
< 0.1	68	80		THEO	[79] SHROCK	80

[66] In the beta spectrum from tritium β decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For m_{ν_j} <1 keV, their upper limit on $|U_{1j}|^2$ becomes less

[67] BERMAN 93 uses an iron-free intermediate-image magnetic spectrometer to measure ^{35}S β decay over a large portion of the spectrum. Paper reports $(0.01 \pm 0.15)\%$; above result revised by author on basis of analysis refinements.

[68] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of ^{3}H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{1j}|^2$ as a function of m_{ν_j} in the range from 13.5 keV to 17.5 keV. Typical upper limits are listed above. They report that this experiment in combination with BAHRAN 92 gives an upper limit of 2.4×10^{-3} at the 99% CL. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[69] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of ^{35}S and ^{14}C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."

[70] OHSHIMA 93 is the full data analysis from this experiment. The above limit on the mixing strength for a 17 keV neutrino is obtained from the measurement $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$ by taking zero as the best estimate and ignoring physical boundaries; see discussion in HOLZSCHUH 92B for a comparison of methods. An earlier report of this experiment was given in KAWAKAMI 92.

[71] WIETFELDT 93 is an extension of the NORMAN 91 experiment. However, whereas NORMAN 91 reported indications for the emission of a neutrino with mass $m_{\nu_j} = 21 \pm 2$ keV and coupling strength $= 0.0085 \pm 0.0045$, the present experiment states that "We find no evidence for emission of a neutrino in the mass range 5–25 keV. In particlular, a 17 keV neutrino with $\sin^2\theta$ ($|U_{1j}|^2$ in our notation) $= 0.008$ is excluded at the 7σ level." The listed limits can be obtained from the paper's Fig. 4. The authors acknowledge that this conclusion contradicts the one reported in NORMAN 91, based on a smaller data sample. In further tests, WIETFELDT 95 have shown that "the observed distortion was most likely caused by systematic effects... A new measurement with a smaller data sample shows no sign of this distortion."

[72] CHEN 92 is a continuation and improvement of the Boehm *et al.* Caltech iron-free magnetic spectrometer experiment searching for emission of massive neutrinos in ^{35}S decay (MARKEY 85). The upper limit on $|U_{1j}|^2$ for $m_{\nu_j} = 17$ keV comes from the measurement $|U_{1j}|^2 = (-0.5 \pm 1.4) \times 10^{-3}$. The authors state that their results "rule out, at the 6σ level, a 17 keV neutrino admixed at 0.85% (*i.e.* with $|U_{1j}|^2 = 0.85 \times 10^{-2}$," the level claimed by Hime and Jelly in HIME 91. They also state that "our data show no evidence for a heavy neutrino with a mass between 12 and 22 keV" with substantial admixture in the weak admixture in the weak eigenstate ν_e; see their Fig. 4 for a graphical set of measured values of $|U_{1j}|^2$ for various hypothetical values of m_{ν_j} in this range.

[73] KAWAKAMI 92 experiment final results are given in OHSHIMA 93. The upper limit is improved to 0.73×10^{-3}, based on $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$. Ohshima notes that the result is 22σ away from the value $|U_{1j}|^2 = 1\%$.

[74] BORGE 86 results originally presented as evidence against the SIMPSON 85 claim of a 17 keV antineutrino emitted with $|U_{1j}|^2 = 0.03$ in ^{3}H decay.

[75] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.

[76] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.

[77] Application of kink search test to tritium β decay Kurie plot.

[78] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.

[79] Application of test to search for kinks in β decay Kurie plots.

Searches for Decays of Massive ν

Limits on $|U_{1j}|^2$ as function of m_{ν_j}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-5}$	95	[80] ABREU	97I	DLPH	m_{ν_j}=6 GeV
$<3 \times 10^{-5}$	95	[80] ABREU	97I	DLPH	m_{ν_j}=50 GeV
$<1.8 \times 10^{-3}$	90	[81] HAGNER	95	MWPC	$m_{\nu_h} = 1.5$ MeV
$<2.5 \times 10^{-4}$	90	[81] HAGNER	95	MWPC	$m_{\nu_h} = 4$ MeV
$<4.2 \times 10^{-3}$	90	[81] HAGNER	95	MWPC	$m_{\nu_h} = 9$ MeV
$<1 \times 10^{-5}$	90	[82] BARANOV	93		m_{ν_j}= 100 MeV
$<1 \times 10^{-6}$	90	[82] BARANOV	93		m_{ν_j}= 200 MeV
$<3 \times 10^{-7}$	90	[82] BARANOV	93		m_{ν_j}= 300 MeV
$<2 \times 10^{-7}$	90	[82] BARANOV	93		m_{ν_j}= 400 MeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	$m_{\nu_j} = 20$ GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	$m_{\nu_j} = 40$ GeV
all values ruled out	95	[83] BURCHAT	90	MRK2	$m_{\nu_j} < 19.6$ GeV
$<1 \times 10^{-10}$	95	[83] BURCHAT	90	MRK2	$m_{\nu_j} = 22$ GeV
$<1 \times 10^{-11}$	95	[83] BURCHAT	90	MRK2	$m_{\nu_j} = 41$ GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_j}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_j}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_j}=6 GeV

$<1.2 \times 10^{-7}$	90	BERNARDI 88	CNTR	m_{ν_j}=100 MeV
$<1 \times 10^{-8}$	90	BERNARDI 88	CNTR	m_{ν_j}=200 MeV
$<2.4 \times 10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_j}=300 MeV
$<2.1 \times 10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_j}=400 MeV
$<2 \times 10^{-2}$	68	[84] OBERAUER 87		m_{ν_j}=1.5 MeV
$<8 \times 10^{-4}$	68	[84] OBERAUER 87		m_{ν_j}=4.0 MeV
$<8 \times 10^{-3}$	90	BADIER 86	CNTR	m_{ν_j}=400 MeV
$<8 \times 10^{-5}$	90	BADIER 86	CNTR	m_{ν_j}=1.7 GeV
$<8 \times 10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_j}=100 MeV
$<4 \times 10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI 86	CNTR	m_{ν_j}=400 MeV
$<3 \times 10^{-5}$	90	DORENBOS... 86	CNTR	m_{ν_j}=150 MeV
$<1 \times 10^{-6}$	90	DORENBOS... 86	CNTR	m_{ν_j}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS... 86	CNTR	m_{ν_j}=1.6 GeV
$<7 \times 10^{-7}$	90	[85] COOPER-... 85	HLBC	m_{ν_j}=0.4 GeV
$<8 \times 10^{-8}$	90	[85] COOPER-... 85	HLBC	m_{ν_j}=1.5 GeV
$<1 \times 10^{-2}$	90	[86] BERGSMA 83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	[86] BERGSMA 83B	CNTR	m_{ν_j}=110 MeV
$<6 \times 10^{-7}$	90	[86] BERGSMA 83B	CNTR	m_{ν_j}=410 MeV
$<1 \times 10^{-5}$	90	GRONAU 83		m_{ν_j}=160 MeV
$<1 \times 10^{-6}$	90	GRONAU 83		m_{ν_j}=480 MeV

[80] ABREU 97I long-lived ν_j analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[81] HAGNER 95 obtain limits on heavy neutrino admixture from the decay $\nu_h \rightarrow \nu_e e^+ e^-$ at a nuclear reactor for the ν_h mass range 2–9 MeV.

[82] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[83] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[84] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' e e$ decay mode using reactor (anti)neutrinos.

[85] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[86] BERGSMA 83B also quote limits on $|U_{13}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Limits on $|U_{2j}|^2$ as Function of m_{ν_j}

Peak search test

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$< 1\text{–}10 \times 10^{-4}$		[87] BRYMAN 96	CNTR	m_{ν_x} = 30–33.91 MeV
$>10^{-16}$		[88] ARMBRUSTER 95	KARM	m_{ν_x} = 33.9 MeV
$< 4 \times 10^{-7}$	95	[89] BILGER 95	LEPS	$m_{\overline{\nu}_x}$ = 33.9 MeV
$< 7 \times 10^{-8}$	95	[89] BILGER 95	LEPS	m_{ν_x} = 33.9 MeV
$< 2.6 \times 10^{-8}$	95	[89] DAUM 95B	TOF	m_{ν_x} = 33.9 MeV
$< 2 \times 10^{-2}$	90	DAUM 87		m_{ν_j}=1 MeV
$< 1 \times 10^{-3}$	90	DAUM 87		m_{ν_j}=2 MeV
$< 6 \times 10^{-5}$	90	DAUM 87		3 MeV < m_{ν_j} < 19.5 MeV
$< 3 \times 10^{-2}$	90	[90] MINEHART 84		m_{ν_j}=2 MeV
$< 1 \times 10^{-3}$	90	[90] MINEHART 84		m_{ν_j}=4 MeV
$< 3 \times 10^{-4}$	90	[90] MINEHART 84		m_{ν_j}=10 MeV
$< 5 \times 10^{-6}$	90	[91] HAYANO 82		m_{ν_j}=330 MeV
$< 1 \times 10^{-4}$	90	[91] HAYANO 82		m_{ν_j}=70 MeV
$< 9 \times 10^{-7}$	90	[91] HAYANO 82		m_{ν_j}=250 MeV
$< 1 \times 10^{-1}$	90	[90] ABELA 81		m_{ν_j}=4 MeV
$< 7 \times 10^{-5}$	90	[90] ABELA 81		m_{ν_j}=10.5 MeV
$< 2 \times 10^{-4}$	90	[90] ABELA 81		m_{ν_j}=11.5 MeV
$< 2 \times 10^{-5}$	90	[90] ABELA 81		m_{ν_j}=16–30 MeV
$< 2 \times 10^{-5}$	95	[91] ASANO 81		m_{ν_j}=170 MeV
$< 3 \times 10^{-6}$	95	[91] ASANO 81		m_{ν_j}=210 MeV
$< 3 \times 10^{-6}$	95	[91] ASANO 81		m_{ν_j}=230 MeV
$< 6 \times 10^{-6}$	95	[92] ASANO 81		m_{ν_j}=240 MeV
$< 5 \times 10^{-7}$	95	[92] ASANO 81		m_{ν_j}=280 MeV
$< 6 \times 10^{-6}$	95	[92] ASANO 81		m_{ν_j}=300 MeV
$< 1 \times 10^{-2}$	95	[90] CALAPRICE 81		m_{ν_j}=7 MeV
$< 3 \times 10^{-3}$	95	[90] CALAPRICE 81		m_{ν_j}=33 MeV
$< 1. \times 10^{-4}$	68	[93] SHROCK 81	THEO	m_{ν_j}=13 MeV
$< 3 \times 10^{-5}$	68	[93] SHROCK 81	THEO	m_{ν_j}=33 MeV
$< 6 \times 10^{-3}$	68	[94] SHROCK 81	THEO	m_{ν_j}=80 MeV
$< 5 \times 10^{-3}$	68	[94] SHROCK 81	THEO	m_{ν_j}=120 MeV

[87] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay. The reported value is the upper limit for the branching ratio, $< 4\text{–}6 \times 10^{-5}$ (90%CL). They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise unconventional neutrino.

[88] ARMBRUSTER 95 study the reactions ${}^{12}\mathrm{C}(\nu_e,e^-)\,{}^{12}\mathrm{N}$ and ${}^{12}\mathrm{C}(\nu,\nu')\,{}^{12}\mathrm{C}^*$ induced by neutrinos from π^+ and μ^+ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where ν_x is a neutral weakly interacting particle with mass ≈ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.

[89] From experiments of π^+ and π^- decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).

[90] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[91] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[92] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.

[93] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[94] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu, \nu_\mu$ decay.

Peak Search in Muon Capture

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*	*COMMENT*
$<1 \times 10^{-1}$	DEUTSCH 83	m_{ν_j}=45 MeV
$<7 \times 10^{-3}$	DEUTSCH 83	m_{ν_j}=70 MeV
$<1 \times 10^{-1}$	DEUTSCH 83	m_{ν_j}=85 MeV

Searches for Decays of Massive ν

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<2 \times 10^{-5}$	95	[95] ABREU 97I	DLPH	m_{ν_j}=6 GeV
$<3 \times 10^{-5}$	95	[95] ABREU 97I	DLPH	m_{ν_j}=50 GeV
$<3 \times 10^{-6}$	90	GALLAS 95	CNTR	m_{ν_j} = 1 GeV
$<3 \times 10^{-5}$	90	[96] VILAIN 95C	CHM2	m_{ν_j} = 2 GeV
$<6.2 \times 10^{-8}$	95	ADEVA 90S	L3	m_{ν_j} = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA 90S	L3	m_{ν_j} = 40 GeV
all values ruled out	95	[97] BURCHAT 90	MRK2	m_{ν_j} < 19.6 GeV
$<1 \times 10^{-10}$	95	[97] BURCHAT 90	MRK2	m_{ν_j} = 22 GeV
$<1 \times 10^{-11}$	95	[97] BURCHAT 90	MRK2	m_{ν_j} = 41 GeV
all values ruled out	95	DECAMP 90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP 90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-4}$	90	[98] KOPEIKIN 90	CNTR	m_{ν_j} = 5.2 MeV
$<5 \times 10^{-3}$	90	AKERLOF 88	HRS	m_{ν_j}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF 88	HRS	m_{ν_j}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF 88	HRS	m_{ν_j}=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI 88	CNTR	m_{ν_j}=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_j}=300 MeV
$<4 \times 10^{-4}$	90	[99] MISHRA 87	CNTR	m_{ν_j}=1.5 GeV
$<4 \times 10^{-3}$	90	[99] MISHRA 87	CNTR	m_{ν_j}=2.5 GeV
$<0.9 \times 10^{-2}$	90	[99] MISHRA 87	CNTR	m_{ν_j}=5 GeV
<0.1	90	[99] MISHRA 87	CNTR	m_{ν_j}=10 GeV
$<8 \times 10^{-4}$	90	BADIER 86	CNTR	m_{ν_j}=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER 86	CNTR	m_{ν_j}=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI 86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS... 86	CNTR	m_{ν_j}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS... 86	CNTR	m_{ν_j}=1600 MeV
$<0.8 \times 10^{-5}$	90	[100] COOPER-... 85	HLBC	m_{ν_j}=0.4 GeV
$<1.0 \times 10^{-7}$	90	[100] COOPER-... 85	HLBC	m_{ν_j}=1.5 GeV

[95] ABREU 97I long-lived ν_j analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[96] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.

[97] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[98] KOPEIKIN 90 find no m_{ν_j} in the interval 1–6.3 MeV at 90%CL for maximal mixing.

[99] See also limits on $|U_{3j}|$ from WENDT 87.

[100] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{3J}|^2$ as a Function of m_{ν_J}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-5}$	95	[101] ABREU	97I	DLPH	m_{ν_j}=6 GeV
$<3 \times 10^{-5}$	95	[101] ABREU	97I	DLPH	m_{ν_j}=50 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_j} = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_j} = 40 GeV
all values ruled out	95	[102] BURCHAT	90	MRK2	m_{ν_j} < 19.6 GeV
$<1 \times 10^{-10}$	95	[102] BURCHAT	90	MRK2	m_{ν_j} = 22 GeV
$<1 \times 10^{-11}$	95	[102] BURCHAT	90	MRK2	m_{ν_j} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF	88	HRS	m_{ν_j}=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF	88	HRS	m_{ν_j}=4.5 GeV

[101] ABREU 97I long-lived ν_j analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.

[102] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{aJ}|^2$

Where $a = 1, 2$ from ρ parameter in μ decay.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_j}=10 MeV
$<2 \times 10^{-3}$	68	SHROCK	81B	THEO	m_{ν_j}=40 MeV
$<4 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_j}=70 MeV

Limits on $|U_{1J} \times U_{2J}|$ as Function of m_{ν_J}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-5}$	90	[103] BARANOV	93		m_{ν_j}= 80 MeV
$<3 \times 10^{-6}$	90	[103] BARANOV	93		m_{ν_j}= 160 MeV
$<6 \times 10^{-7}$	90	[103] BARANOV	93		m_{ν_j}= 240 MeV
$<2 \times 10^{-7}$	90	[103] BARANOV	93		m_{ν_j}= 320 MeV
$<9 \times 10^{-5}$	90	BERNARDI	86	CNTR	m_{ν_j}=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86	CNTR	m_{ν_j}=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B	CNTR	m_{ν_j}=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B	CNTR	m_{ν_j}=370 MeV

[103] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

(E) Solar ν Experiments

SOLAR NEUTRINOS

Revised February 1998 by K. Nakamura (KEK, High Energy Accelerator Research Organization, Japan).

The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions which generate solar energy, and whose combined effect is

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV} - E_\nu\ , \qquad (1)$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. Each neutrino-producing reaction, the resulting flux, and contributions to the event rates in chlorine and gallium solar-neutrino experiments predicted by the recent Bahcall and Pinsonneault standard solar model (SSM) calculation [1] are listed in Table 1. This SSM is regarded as the best with helium and heavy-element diffusion. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from the SSM calculation by Bahcall and Ulrich [2]. Recently, the SSM has been shown to predict accurately the helioseismological sound velocities with a precision of 0.1% rms throughout essentially the entire Sun, greatly strengthening the confidence in the solar model [3].

Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes and event rates in chlorine and gallium solar-neutrino expreiments predicted by Bahcall and Pinsonneault [1] are listed in the third, fourth, and fifth columns respectively.

		BAHCALL 95B [1]		
Reaction	Abbr.	Flux ($\text{cm}^{-2}\ \text{s}^{-1}$)	Cl (SNU*)	Ga (SNU*)
$pp \rightarrow d e^+ \nu$	pp	$5.91(1.00^{+0.01}_{-0.01}) \times 10^{10}$	—	69.7
$pe^-p \rightarrow d \nu$	pep	$1.40(1.00^{+0.01}_{-0.02}) \times 10^{8}$	0.22	3.0
${}^3\text{He}\, p \rightarrow {}^4\text{He}\, e^+ \nu$	hep	1.21×10^3		
${}^7\text{Be}\, e^- \rightarrow {}^7\text{Li}\, \nu + (\gamma)$	${}^7\text{Be}$	$5.15(1.00^{+0.06}_{-0.07}) \times 10^{9}$	1.24	37.7
${}^8\text{B} \rightarrow {}^8\text{Be}^*\, e^+ \nu$	${}^8\text{B}$	$6.62(1.00^{+0.14}_{-0.17}) \times 10^{6}$	7.36	16.1
${}^{13}\text{N} \rightarrow {}^{13}\text{C}\, e^+ \nu$	${}^{13}\text{N}$	$6.18(1.00^{+0.17}_{-0.20}) \times 10^{8}$	0.11	3.8
${}^{15}\text{O} \rightarrow {}^{15}\text{N}\, e^+ \nu$	${}^{15}\text{O}$	$5.45(1.00^{+0.19}_{-0.22}) \times 10^{8}$	0.37	6.3
${}^{17}\text{F} \rightarrow {}^{17}\text{O}\, e^+ \nu$	${}^{17}\text{F}$	$6.48(1.00^{+0.15}_{-0.19}) \times 10^{6}$		
Total			$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

Observation of solar neutrinos directly addresses the SSM and, more generally, the theory of stellar structure and evolution which is the basis of the SSM. The Sun as a well-defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the very long distance from the Sun to the Earth. In fact, the currently available solar-neutrino data seem to require such neutrino properties, if one tries to understand them consistently.

So far, four solar-neutrino experiments published the results. In addition, a new solar-neutrino experiment (Super-Kamiokande) started observation in 1996. Three of them are radiochemical experiments using ^{37}Cl (Homestake in USA) or ^{71}Ga (GALLEX at Gran Sasso in Italy and SAGE at Baksan in Russia) to capture neutrinos: ${}^{37}\text{Cl}\ \nu_e \rightarrow {}^{37}\text{Ar}\ e^-$ (threshold 814 keV) or ${}^{71}\text{Ga}\ \nu_e \rightarrow {}^{71}\text{Ge}\ e^-$ (threshold 233 keV). The produced ^{37}Ar and ^{71}Ge are both radioactive nuclei, with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are extracted and introduced into a low-background proportional counter, and are counted for a sufficiently long period to determine the exponentially decaying signal and a

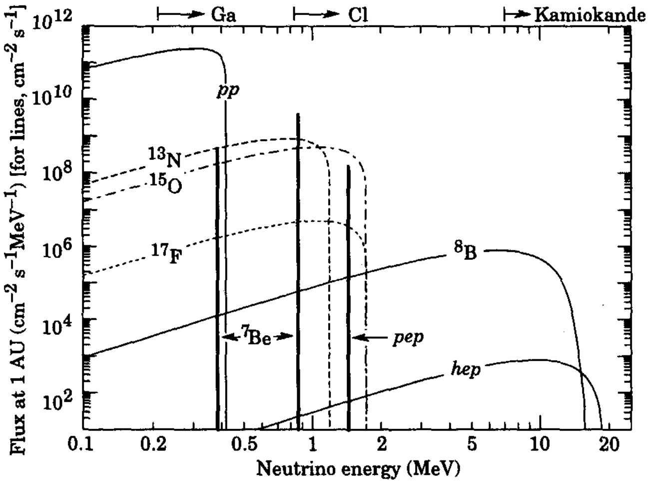

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number cm^{-2}s^{-1}MeV^{-1} at one astronomical unit, and the line fluxes are given in number cm^{-2}s^{-1}. Spectra for the *pp* chain are shown by solid lines, and those for the CNO chain by dotted or dashed lines. (Courtesy of J.N. Bahcall, 1995.)

constant background. In the chlorine experiment, the dominant contribution comes from ^{8}B neutrinos, but ^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, almost half of the capture rate in the gallium experiments is due to other solar neutrinos.

The other experiments are real-time experiments utilizing νe scattering in a large water-Čerenkov detector (Kamiokande and Super-Kamiokande in Japan). These experiments take advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to the high thresholds (7 MeV in Kamiokande and 6.5 MeV at present in Super-Kamiokande) the experiments observe pure ^{8}B solar neutrinos (*hep* neutrinos contribute negligibly).

Solar neutrinos were first observed in the Homestake chlorine experiment in the late 1960's. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction provided nothing happens to the electron neutrinos after they are created in the solar interior. This deficit has been called "the solar-neutrino problem."

The Kamiokande-II Collaboration started observing the ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos (no directional information is available in radiochemical solar-neutrino experiments.) The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the day time and nighttime. The Kamiokande-II experiment came to an end at the beginning of 1995, and a 50-kton second-generation solar-neutrino detector Super-Kamiokande started observation in April, 1996.

GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE, after the initial confusion which is ascribed to statistics by the group, observed a similar capture rate to that of GALLEX. Both GALLEX and SAGE groups tested the overall detector response with intense man-made ^{51}Cr neutrino sources, and observed good agreement between the measured ^{71}Ge production rate and that predicted from the source activity, demonstrating the reliability of these experiments.

The most recent published results on the average capture rates or flux from these experiments are listed in Table 2 and compared to the results from SSM calculations which are taken from "Lepton Particle Listings (E) Solar ν Experiments" in this edition of "Review of Particle Physics." In these calculations, BAHCALL 95B [1] and DAR 96 [9] take into account helium and heavy-element diffusion, but other calculations do not. SSM calculations give essentially the same results for the same input parameters and physics. The BAHCALL 95B [1] model and the TURCK-CHIEZE 93B [10] model differ primarily in that BAHCALL 95B [1] includes element diffusion. DAR 96 [9] model differs significantly from the BAHCALL 95B [1] model mostly due to the use of nonstandard reaction rates, the different treatments of diffusion and the equation of state.

There was a controversy whether the ^{37}Cl capture rate showed possible time variation, anticorrelated with the sunspot numbers which represent the 11-year solar-activity cycle. However, Walther recently argued that the claimed significant anticorrelation is due to a statistical fallacy [7]. Also, eight years of Kamiokande-II solar-neutrino observations covering an entire period of solar cycle 22 [8] does not show evidence for a statistically significant correlation or anticorrelation between the solar-neutrino flux and sunspot number.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from the SSM calculations except DAR 96 [9]. The DAR 96 [9] model predicts the ^{8}B solar-neutrino flux which is consistent with the Kamiokande-II result, but even this model predicts ^{37}Cl and ^{71}Ga capture rates significantly larger than the Homestake, GALLEX, and SAGE results. Is there any possible consistent explanation of all the results of solar-neutrino observations in the framework of the standard solar model? This is difficult because the Homestake result and the Kamiokande result, taken at face value, are mutually inconsistent if one assumes standard neutrino spectra. That is, with the reduction factor of the ^{8}B solar-neutrino flux

Table 2: Recent results from the four solar-neutrino experiments and a comparison with theoretical solar-model predictions. Solar model calculations are also presented. The evolution of these results over the years gives some feeling for their robustness as the models have become more sophisticated and complete.

	^{37}Cl→^{37}Ar (SNU)	^{71}Ga→^{71}Ge (SNU)	^{8}B ν flux (10^6cm^{-2}s^{-1})
Homestake			
(DAVIS 89)[4]	2.33 ± 0.25	—	—
GALLEX			
(HAMPEL 96)[5]	—	$69.7 \pm 6.7^{+3.9}_{-4.5}$	—
SAGE			
(ABDURASHI...94)[6]	—	73^{+18+5}_{-16-7}	—
Kamiokande			
(FUKUKDA 96)[8]	—	—	$2.80 \pm 0.19 \pm 0.33$
(DAR 96)[9]	4.1 ± 1.2	115 ± 6	2.49
(BAHCALL 95B)[1]	$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}	$6.6(1.00^{+0.14}_{-0.17})$
(TURCK-CHIEZE 93B)[10]	6.4 ± 1.4	123 ± 7	4.4 ± 1.1
(BAHCALL 92)[11]	$8.0 \pm 3.0^{\dagger}$	$132^{+21}_{-17}{}^{\dagger}$	$5.69(1.00 \pm 0.43)^{\dagger}$
(BAHCALL 88)[2]	$7.9 \pm 2.6^{\dagger}$	$132^{+20}_{-17}{}^{\dagger}$	$5.8(1.00 \pm 0.37)^{\dagger}$
(TURCK-CHIEZE 88)[12]	5.8 ± 1.3	125 ± 5	$3.8(1.00 \pm 0.29)$
(FILIPPONE 83)[13]	5.6	—	—
(BAHCALL 82)[14]	$7.6 \pm 3.3^{\dagger}$	$106^{+13}_{-8}{}^{\dagger}$	5.6
(FILIPPONE 82)[15]	7.0 ± 3.0	111 ± 13	4.8
(FOWLER 82)[16]	6.9 ± 1.0	—	—
(BAHCALL 80)[17]	7.3	—	—

[*] 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

[†] "3σ" errors.

as determined from the Kamiokande result, the Homestake ^{37}Cl capture rate would be oversaturated, and there would be no room to accommodate the ^{7}Be solar neutrinos. This makes astrophysical solutions untenable because ^{8}B nuclei are produced from ^{7}Be nuclei in the Sun.

Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found (see for example, Refs. 18–20)

- that both the comparison of the Kamiokande and gallium results and the comparison of the gallium and chlorine results also indicate strong suppression of the ^{7}Be solar-neutrino flux, and
- that not only the SSM but also nonstandard solar models are incompatible with the observed data.

In view of the above situation, it is attractive to invoke nontrivial neutrino properties. Neutrino oscillation in matter (MSW mechanism) is particularly attractive in explaining all the experimental data on the average solar-neutrino flux consistently, without any *a priori* assumptions or fine tuning. Several authors made extensive MSW analyses using all the existing data and ended up with similar results. For example, Hata and Langacker [19] analyzed the solar-neutrino data as of 1996 in terms of two-flavor oscillations, including the preliminary result from Super-Kamiokande [21] on the average ^{8}B solar-neutrino flux which is consistent with the Kamiokande-II result. They obtained viable solutions for the BAHCALL 95B [1] SSM: the small-mixing solution ($\Delta m^2 \sim 5 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 8 \times 10^{-3}$) and the large-mixing solution ($\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2 and $\sin^2 2\theta \sim 0.6$). Vacuum oscillations also provide solutions ($\Delta m^2 = (5\text{–}8) \times 10^{-11}$ eV^2 and $\sin^2 2\theta = 0.65 - 1$).

Assuming that the solution to the solar-neutrino problem be provided by some nontrivial neutrino properties, how can one discriminate various scenarios? The measurements of energy spectrum of the solar neutrinos and the day-night flux difference, and the measurement of solar-neutrino flux by utilizing neutral-current reactions are key issues. The MSW small-mixing solution causes the energy-spectrum distortion, while the MSW large-angle solution causes the day-night flux difference. If the flux measured by neutral-current reactions is consistent with the SSM prediction, and larger than that measured by charged-current reactions, it is a clear indication of neutrino oscillations.

Two high-statistics solar-neutrino experiments, Sudbury Neutrino Observatory (SNO) and Super-Kamiokande are expected to provide such results within a few years. Super-Kamiokande is sensitive to the solar-neutrino spectrum through measurement of recoil electron energy. SNO, which is expected to be completed in 1998, will use 1,000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse beta decay ($\nu_e d \rightarrow e^- pp$) and neutral current interactions ($\nu_x d \rightarrow \nu_x pn$). In addition, νe scattering events will also be measured. The Borexino experiment with 300 tons of ultrapure liquid scintillator is approved for the Gran Sasso. The primary purpose of this experiment is the measurement of the ^{7}Be solar neutrino flux, whose possible deficit is now a key question, by lowering the detection threshold for the recoil electrons to 250 keV. Also, the vacuum-oscillations cause seasonal variation of the ^{7}Be solar neutrino flux. It is hoped that these new experiments will finally provide the key to solving the different solar-neutrino problems raised by the first-generation experiments.

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1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
$(2.80 \pm 0.19 \pm 0.33)\times10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	[104] FUKUDA 96	KAMI	$^8B\nu$ flux
$(2.70 \pm 0.27)\times10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	[104] FUKUDA 96	KAMI	$^8B\nu$ flux (day)
$(2.87^{+0.27}_{-0.26})\times10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	[104] FUKUDA 96	KAMI	$^8B\nu$ flux (night)
$69.7 \pm 6.7^{+3.9}_{-4.5}$ SNU	[105] HAMPEL 96	GALX	$^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge}$
$73^{+18}_{-16}{}^{+5}_{-7}$ SNU	[106] ABDURASHI... 94	SAGE	$^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge}$
2.33 ± 0.25 SNU	[107] DAVIS 89	HOME	^{37}Cl radiochemical

[104] FUKUDA 96 results are for a total of 2079 live days with Kamiokande II and III from January 1987 through February 1995, covering the entire solar cycle 22, with threshold $E_e > 9.3$ MeV (first 449 days), > 7.5 MeV (middle 794 days), and > 7.0 MeV (last 836 days). These results update the HIRATA 90 result for the average ^{8}B solar-neutrino flux and HIRATA 91 result for the day-night variation in the ^{8}B solar-neutrino flux. The total data sample was also analyzed for short-term variations: within experimental errors, no strong correlation of the solar-neutrino flux with the sunspot numbers was found.

[105] HAMPEL 96 reports the combined result for GALLEX I+II+III (53 runs in total), which updates the ANSELMANN 95B result. The GALLEX III result (14 runs) is $53.9 \pm 10.6 \pm 3.1$ SNU, which is "15.8 SNU below but statistically compatible with the new combined result." The total run data, covering the period 14 May 1991 through 4 October 1995, are consistent with a ^{71}Ge production rate constant in time, but "the confidence with which some kind of periodic or sporadic variability may be excluded has decreased as a result of the statistical departure of GALLEX III." HAMPEL 96 also reports the second calibration run using a strong ^{51}Cr source. The result combined with the ANSELMANN 95 data was found to be 92 ± 8 for the (measured)/(expected) Cr induced ^{71}Ge rate.

[106] ABDURASHITOV 94 result is for a total of 15 runs from January 1990 through May 1992, using 30 tons of metallic gallium for the first 7 runs, increased to 57 tons for the rest of 8 runs. The first 5 runs in 1990 yielded $40^{+31}_{-38}{}^{+5}_{-7}$ SNU which updates the ABAZOV 91B result.

[107] DAVIS 89 is the average from the ^{37}CL experiment at the Homestake Mine (HOME) from 1970–1988. Earlier averages are given in the references therein.

(F) Astrophysical neutrino observations

Neutrinos and antineutrinos produced in the atmosphere induce μ-like and e-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as μ/e. It has the advantage that that systematic effects, such as flux uncertainty, tend to cancel, for both experimental and theoretical values of the ratio. The "ratio of the ratios" of experimental to theoretical μ/e, $R(\mu/e)$, or that of experimental to theoretical μ/total, $R(\mu/\mathrm{total})$ with total = $\mu+e$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions.

$R(\mu/e)$ = (Measured Ratio μ/e) / (Expected Ratio μ/e)

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.72 \pm 0.19^{+0.05}_{-0.07}$	[108] ALLISON 97	SOU2	Calorimeter
	[109] FUKUDA 96B	KAMI	Water Cerenkov
$1.00 \pm 0.15 \pm 0.08$	[110] DAUM 95	FREJ	Calorimeter
$0.60^{+0.06}_{-0.05} \pm 0.05$	[111] FUKUDA 94	KAMI	sub-GeV
$0.57^{+0.08}_{-0.07} \pm 0.07$	[112] FUKUDA 94	KAMI	multi-Gev
	[113] BECKER-SZ... 92B	IMB	Water Cerenkov

[108] ALLISON 97 result is based on an exposure of 1.52 kton yr. ALLISON 97 also studied the background due to interaction of neutrons or photons produced by muon interactions in the rock surrounding the detector. This background is shown not to produce the low values of $R(\mu/e)$.

[109] FUKUDA 96B studied neutron background in the atmospheric neutrino sample observed in the Kamiokande detector. No evidence for the background contamination was found.

[110] DAUM 95 results are based on an exposure of 2.0 kton yr which includes the data used by BERGER 90B. This ratio is for the contained and semicontained events. DAUM 95 also report $R(\mu/e) = 0.99 \pm 0.13 \pm 0.08$ for the total neutrino induced data sample which includes upward going stopping muons and horizontal muons in addition to the contained and semicontained events.

[111] FUKUDA 94 result is based on an exposure of 7.7 kton yr and updates the HIRATA 92 result. The analyzed data sample consists of fully contained e-like events with $0.1 < p_e < 1.33$ GeV/c and fully-contained μ-like events with $0.2 < p_\mu < 1.5$ GeV/c.

[112] FUKUDA 94 analyzed the data sample consisting of fully contained events with visible energy > 1.33 GeV and partially contained μ-like events.

[113] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atomospheric neutrinos) as $0.36 \pm 0.02 \pm 0.02$, as compared with expected fraction $0.51 \pm 0.01 \pm 0.05$. After cutting the energy range to the Kamiokande limits, BEIER 92 finds $R(\mu/e)$ very close to the Kamiokande value.

$R(\nu_\mu)$ = (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.73 \pm 0.09 \pm 0.06$	[114] AHLEN 95	MCRO	Streamer tubes
	[115] CASPER 91	IMB	Water Cherenkov
	[116] AGLIETTA 89	NUSX	
0.95 ± 0.22	[117] BOLIEV 81		Baksan
0.62 ± 0.17	CROUCH 78		Case Western/UCI

[114] AHLEN 95 result is for all nadir angles. The lower cutoff on the muon energy is 1 GeV. The errors are statistical / systematic. The Monte Carlo flux error is ±0.12.

[115] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering ($\approx \nu_\mu$ induced) fraction is $0.41 \pm 0.03 \pm 0.02$, as compared with expected 0.51 ± 0.05 (syst).

[116] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report $\rho(\mathrm{measured}) = \rho(\mathrm{expected}) = 0.96^{+0.32}_{-0.28}$.

[117] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\rightarrow \nu_\mu$ type oscillation.

$R(\mu/\mathrm{total})$ = (Measured Ratio μ/total) / (Expected Ratio μ/total)

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.1^{+0.07}_{-0.12} \pm 0.11$	[118] CLARK 97	IMB	multi-GeV

[118] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_e \leftrightarrow \nu_\mu$)

For a review see BAHCALL 89.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.5		[119] CLARK 97	IMB	$\Delta(m^2) > 0.1$ eV^2
>0.55	90	[120] FUKUDA 94	KAMI	$\Delta(m^2) = 0.007$–0.08 ev^2
<0.47	90	[121] BERGER 90B	FREJ	$\Delta(m^2) > 1$ eV^2
<0.14	90	LOSECCO 87	IMB	$\Delta(m^2) = 0.00011$ eV^2

[119] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[120] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[121] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_e \leftrightarrow \nu_\mu$)

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<980		[122] CLARK 97	IMB
$700 < \Delta(m^2) < 7000$	90	[123] FUKUDA 94	KAMI
<150	90	[124] BERGER 90B	FREJ

[122] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[123] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[124] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$)

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.9	99	[125] SMIRNOV 94	THEO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
<0.7	99	[125] SMIRNOV 94	THEO	$\Delta(m^2) < 10^{-11}$ eV^2

[125] SMIRNOV 94 analyzed the data from SN 1987A using stellar-collapse models. They also give less stringent upper limits on $\sin^2 2\theta$ for $10^{-11} < \Delta(m^2) < 3 \times 10^{-7}$ eV^2 and $10^{-5} < \Delta(m^2) < 3 \times 10^{-4}$ eV^2. The same results apply to $\overline{\nu}_e \leftrightarrow \overline{\nu}_\tau$, ν_μ, and ν_τ.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.7		[126] CLARK 97	IMB	$\Delta(m^2) > 0.1$ eV^2
>0.65	90	[127] FUKUDA 94	KAMI	$\Delta(m^2) = 0.005$–0.03 eV^2
>0.5	90	[128] BECKER-SZ... 92	IMB	$\Delta(m^2) = 1$–2×10^{-4} eV^2
<0.6	90	[129] BERGER 90B	FREJ	$\Delta(m^2) > 1$ eV^2

[126] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[127] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[128] BECKER-SZENDY 92 uses upward-going muons to search for atomospheric ν_μ oscillations. The fraction of muons which stop in the detector is used to search for deviations in the expected spectrum. No evidence for oscillations is found.

[129] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<1500		[130] CLARK 97	IMB
$500 < \Delta(m^2) < 2500$	90	[131] FUKUDA 94	KAMI
< 350	90	[132] BERGER 90B	FREJ

[130] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[131] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[132] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \to \nu_s$)

ν_s means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3000 (or <550)	90	[133] OYAMA 89	KAMI	Water Cerenkov
< 4.2 or $> 54.$	90	BIONTA 88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[133] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2) = (100\text{–}1000) \times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.

(G) Reactor $\overline{\nu}_e$ disappearance experiments

In most cases, the reaction $\overline{\nu}_e p \to e^+ n$ is observed at different distances from one or more reactors in a complex.

Events (Observed/Expected) from Reactor $\overline{\nu}_e$ Experiments

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.98 \pm 0.04 \pm 0.04$	[134] APOLLONIO 98	CHOZ	Chooz reactors 1.1 km
$0.987 \pm 0.006 \pm 0.037$	[135] GREENWOOD 96		Savannah River, 18.2 m
$1.055 \pm 0.010 \pm 0.037$	[135] GREENWOOD 96		Savannah River, 23.8 m
$0.988 \pm 0.004 \pm 0.05$	ACHKAR 95	CNTR	Bugey reactor, 15 m
$0.994 \pm 0.010 \pm 0.05$	ACHKAR 95	CNTR	Bugey reactor, 40 m
$0.915 \pm 0.132 \pm 0.05$	ACHKAR 95	CNTR	Bugey reactor, 95 m
$0.987 \pm 0.014 \pm 0.027$	[136] DECLAIS 94	CNTR	Bugey reactor, 15 m
$0.985 \pm 0.018 \pm 0.034$	KUVSHINN... 91	CNTR	Rovno reactor
$1.05 \pm 0.02 \pm 0.05$	VUILLEUMIER 82		Gösgen reactor
$0.955 \pm 0.035 \pm 0.110$	[137] KWON 81		$\overline{\nu}_e p \to e^+ n$
0.89 ± 0.15	[137] BOEHM 80		$\overline{\nu}_e p \to e^+ n$
0.38 ± 0.21	[138,139] REINES 80		
0.40 ± 0.22	[138,139] REINES 80		

[134] APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \to e^+ n$ in Gd-loaded scintillator target.

[135] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River.

[136] DECLAIS 94 result based on integral measurement of neutrons only. Result is ratio of measured cross section to that expected in standard *V-A* theory. Replaced by ACHKAR 95.

[137] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.

[138] REINES 80 involves comparison of neutral- and charged-current reactions $\overline{\nu}_e d \to n p \overline{\nu}_e$ and $\overline{\nu}_e d \to n n e^+$ respectively. Combined analysis of reactor $\overline{\nu}_e$ experiments was performed by SILVERMAN 81.

[139] The two REINES 80 values correspond to the calculated $\overline{\nu}_e$ fluxes of AVIGNONE 80 and DAVIS 79 respectively.

——— $\overline{\nu}_e \not\to \overline{\nu}_e$ ———

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0009	90	[140] APOLLONIO 98	CHOZ	Chooz reactors 1.1 km
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	90	[141] GREENWOOD 96		Savannah River
<0.01	90	[142] ACHKAR 95	CNTR	Bugey reactor
<0.0075	90	[143] VIDYAKIN 94		Krasnoyark reactors
<0.0083	90	[143] VIDYAKIN 90		Krasnoyark reactors
<0.04	90	[144] AFONIN 88	CNTR	Rovno reactor
<0.014	68	[145] VIDYAKIN 87		$\overline{\nu}_e p \to e^+ n$
<0.019	90	[146] ZACEK 86		Gösgen reactor
<0.02	90	[147] ZACEK 85		Gösgen reactor
<0.016	90	[148] GABATHULER 84		Gösgen reactor

[140] APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \to e^+ n$ in Gd-loaded scintillator target. This is the most sensitive search in terms of $\Delta(m^2)$ for $\overline{\nu}_e$ disappearance.

[141] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River by observing $\overline{\nu}_e p \to e^+ n$ in a Gd loaded scintillator target. Their region of sensitivity in $\Delta(m^2)$ and $\sin^2 2\theta$ is already excluded by ACHKAR 95.

[142] ACHKAR 95 bound is for L=15, 40, and 95 m.

[143] VIDYAKIN 94 bound is for L=57.0 m, 57.6 m, and 231.4 m. Supersedes VIDYAKIN 90.

[144] AFONIN 86 and AFONIN 87 also give limits on $\sin^2(2\theta)$ for intermediate values of $\Delta(m^2)$. (See also KETOV 92). Supersedes AFONIN 87, AFONIN 86, AFONIN 85, AFONIN 83, and BELENKII 83.

[145] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[146] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m.

[147] See the comment for ZACEK 85 in the section on $\sin^2(2\theta)$ below.

[148] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9 m and new data at 45.9 m.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.02	90	[149] ACHKAR 95	CNTR	For $\Delta(m^2) = 0.6$ eV^2
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18	90	[150] APOLLONIO 98	CHOZ	Chooz reactors 1.1 km
<0.24	90	[151] GREENWOOD 96		
<0.04	90	[151] GREENWOOD 96		For $\Delta(m^2) = 1.0$ eV^2
<0.087	68	[152] VYRODOV 95	CNTR	For $\Delta(m^2) > 2$ eV^2
<0.15	90	[153] VIDYAKIN 94		For $\Delta(m^2) > 5.0 \times 10^{-2}$ eV^2
<0.2	90	[154] AFONIN 88	CNTR	$\overline{\nu}_e p \to e^+ n$
<0.14	68	[155] VIDYAKIN 87		$\overline{\nu}_e p \to e^+ n$
<0.21	90	[156] ZACEK 86		$\overline{\nu}_e p \to e^+ n$
<0.19	90	[157] ZACEK 85		Gösgen reactor
<0.16	90	[158] GABATHULER 84		$\overline{\nu}_e p \to e^+ n$

[149] ACHKAR 95 bound is from data for L=15, 40, and 95 m distance from the Bugey reactor.

[150] APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They

[151] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River by observing $\overline{\nu}_e p \to e^+ n$ in a Gd loaded scintillator target. Their region of sensitivity in $\Delta(m^2)$ and $\sin^2 2\theta$ is already excluded by ACHKAR 95.

[152] The VYRODOV 95 bound is from data for L=15 m distance from the Bugey-5 reactor.

[153] The VIDYAKIN 94 bound is from data for L=57.0 m, 57.6 m, and 231.4 m from three reactors in the Krasnoyark Reactor complex.

[154] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits. Different upper limits on $\sin^2 2\theta$ apply at intermediate values of $\Delta(m^2)$. Supersedes AFONIN 87, AFONIN 85, and BELENKII 83.

[155] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[156] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.

[157] ZACEK 85 gives two sets of bounds depending on what assumptions are used in the data analysis. The bounds in figure 3(a) of ZACEK 85 are progressively poorer for large $\Delta(m^2)$ whereas those of figure 3(b) approach a constant. We list the latter. Both sets of bounds use combination of data from 37.9, 45.9, and 64.7m distance from reactor. ZACEK 85 states "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data, CAVAIGNAC 84) almost completely, thus disproving the indications of neutrino oscillations of CAVAIGNAC 84 with a high degree of confidence."

[158] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.

(H) Accelerator neutrino appearance experiments

——— $\nu_e \to \nu_\tau$ ———

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 9	90	USHIDA 86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<44	90	TALEBZADEH 87	HLBC	BEBC

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.25	90	[159] USHIDA 86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.36	90	TALEBZADEH 87	HLBC	BEBC

[159] USHIDA 86C published result is $\sin^2 2\theta < 0.12$. The quoted result is corrected for a numerical mistake incurred in calculating the expected number of ν_e CC events, normalized to the total number of neutrino interactions (3886) rather than to the total number of ν_μ CC events (1870).

——— $\overline{\nu}_e \to \overline{\nu}_\tau$ ———

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.7	90	[160] FRITZE 80	HYBR	BEBC CERN SPS

[160] Authors give $P(\nu_e \to \nu_\tau) < 0.35$, equivalent to above limit.

——— $\nu_\mu \to \nu_e$ ———

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.09	90	ANGELINI 86	HLBC	BEBC CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.3	90	[161] LOVERRE 96		CHARM/CDHS
<0.9	90	VILAIN 94C	CHM2	CERN SPS
<0.1	90	BLUMENFELD 89	CNTR	
<1.3	90	AMMOSOV 88	HLBC	SKAT at Serpukhov
<0.19	90	BERGSMA 88	CHRM	
		[162] LOVERRE 88	RVUE	
<2.4	90	AHRENS 87	CNTR	BNL AGS
<1.8	90	BOFILL 87	CNTR	FNAL
<2.2	90	[163] BRUCKER 86	HLBC	15-ft FNAL
<0.43	90	AHRENS 85	CNTR	BNL AGS E734
<0.20	90	BERGSMA 84	CHRM	
<1.7	90	ARMENISE 81	HLBC	GGM CERN PS
<0.6	90	BAKER 81	HLBC	15-ft FNAL
<1.7	90	ERRIQUEZ 81	HLBC	BEBC CERN PS
<1.2	95	BLIETSCHAU 78	HLBC	GGM CERN PS
<1.2	95	BELLOTTI 76	HLBC	GGM CERN PS

[161] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[162] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[163] 15ft bubble chamber at FNAL.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
< 3.0	90	[164] LOVERRE 96		CHARM/CDHS
< 2.5	90	AMMOSOV 88	HLBC	SKAT at Serpukhov
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 9.4	90	VILAIN 94C	CHM2	CERN SPS
< 5.6	90	[165] VILAIN 94C	CHM2	CERN SPS
< 16	90	BLUMENFELD 89	CNTR	
< 8	90	BERGSMA 88	CHRM	$\Delta(m^2) \geq 30$ eV^2
		[166] LOVERRE 88	RVUE	
< 10	90	AHRENS 87	CNTR	BNL AGS
< 15	90	BOFILL 87	CNTR	FNAL
< 20	90	[167] ANGELINI 86	HLBC	BEBC CERN PS
20 to 40		[168] BERNARDI 86B	CNTR	$\Delta(m^2)$=5–10
< 11	90	[169] BRUCKER 86	HLBC	15-ft FNAL
< 3.4	90	AHRENS 85	CNTR	BNL AGS E734
<240	90	BERGSMA 84	CHRM	
< 10	90	ARMENISE 81	HLBC	GGM CERN PS
< 6	90	BAKER 81	HLBC	15-ft FNAL
< 10	90	ERRIQUEZ 81	HLBC	BEBC CERN PS
< 4	95	BLIETSCHAU 78	HLBC	GGM CERN PS
< 10	95	BELLOTTI 76	HLBC	GGM CERN PS

[164] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[165] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.

[166] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[167] ANGELINI 86 limit reaches 13×10^{-3} at $\Delta(m^2) \approx 2$ eV^2.

[168] BERNARDI 86B is a typical fit to the data, assuming mixing between two species. As the authors state, this result is in conflict with earlier upper bounds on this type of neutrino oscillations.

[169] 15ft bubble chamber at FNAL.

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID	TECN	COMMENT
<0.14	90	[170] FREEDMAN 93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05–0.08	90	[171] ATHANASSO...96	LSND	LAMPF
0.048–0.090	80	[172] ATHANASSO...95		
<0.07	90	[173] HILL 95		
<0.9	90	VILAIN 94C	CHM2	CERN SPS
<3.1	90	BOFILL 87	CNTR	FNAL
<2.4	90	TAYLOR 83	HLBC	15-ft FNAL
<0.91	90	[174] NEMETHY 81B	CNTR	LAMPF
<1	95	BLIETSCHAU 78	HLBC	GGM CERN PS

[170] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[171] ATHANASSOPOULOS 96 is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly from π^+ decay at rest. $\overline{\nu}_e$ could come from either $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ or $\nu_e \rightarrow \overline{\nu}_e$; our entry assumes the first interpretation. They are detected through $\overline{\nu}_e p \rightarrow e^+ n$ (20 MeV $<E_{e+}<$60 MeV) in delayed coincidence with $np \rightarrow d\gamma$. Authors observe $51 \pm 20 \pm 8$ total excess events over an estimated background 12.5 ± 2.9. ATHANASSOPOULOS 96B is a shorter version of this paper.

[172] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)$%. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[173] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[174] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	95	BLIETSCHAU 78	HLBC	GGM CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0062 \pm 0.0024 \pm 0.0010$		[175] ATHANASSO...96	LSND	LAMPF
0.003–0.012	80	[176] ATHANASSO...95		
<0.006	90	[177] HILL 95		
<4.8	90	VILAIN 94C	CHM2	CERN SPS
<5.6	90	[178] VILAIN 94C	CHM2	CERN SPS
<0.024	90	[179] FREEDMAN 93	CNTR	LAMPF
<0.04	90	BOFILL 87	CNTR	FNAL
<0.013	90	TAYLOR 83	HLBC	15-ft FNAL
<0.2	90	[180] NEMETHY 81B	CNTR	LAMPF

[175] ATHANASSOPOULOS 96 reports $(0.31 \pm 0.12 \pm 0.05)$% for the oscillation probability; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ should be twice this probability. See footnote in preceeding table for further details, and see the paper for a plot showing allowed regions.

[176] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)$%. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[177] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[178] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.

[179] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[180] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID	TECN	COMMENT
<0.075	90	BORODOV... 92	CNTR	BNL E776
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.6	90	[181] ROMOSAN 97	CCFR	FNAL

[181] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<1.8	90	[182] ROMOSAN 97	CCFR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.8	90	[183] MCFARLAND 95	CCFR	FNAL
<3	90	BORODOV... 92	CNTR	BNL E776

[182] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

[183] MCFARLAND 95 state that "This result is the most stringent to date for 250$<\Delta(m^2)<$450 ev^2 and also excludes at 90%CL much of the high $\Delta(m^2)$ region favored by the recent LSND observation." See ATHANASSOPOULOS 95 and ATHANASSOPOULOS 96.

$\nu_\mu \rightarrow \nu_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID	TECN	COMMENT
< 0.9	90	USHIDA 86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 3.3	90	[184] LOVERRE 96		CHARM/CDHS
< 1.4	90	MCFARLAND 95	CCFR	FNAL
< 4.5	90	BATUSOV 90B	EMUL	FNAL
<10.2	90	BOFILL 87	CNTR	FNAL
< 6.3	90	BRUCKER 86	HLBC	15-ft FNAL
< 4.6	90	ARMENISE 81	HLBC	GGM CERN SPS
< 3	90	BAKER 81	HLBC	15-ft FNAL
< 6	90	ERRIQUEZ 81	HLBC	BEBC CERN SPS
< 3	90	USHIDA 81	EMUL	FNAL

[184] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	90	USHIDA 86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.006	90	[185] LOVERRE 96		CHARM/CDHS
<0.0081	90	MCFARLAND 95	CCFR	FNAL
<0.06	90	BATUSOV 90B	EMUL	FNAL
<0.34	90	BOFILL 87	CNTR	FNAL
<0.088	90	BRUCKER 86	HLBC	15-ft FNAL
<0.11	90	BALLAGH 84	HLBC	15-ft FNAL
<0.017	90	ARMENISE 81	HLBC	GGM CERN SPS
<0.06	90	BAKER 81	HLBC	15-ft FNAL
<0.05	90	ERRIQUEZ 81	HLBC	BEBC CERN SPS
<0.013	90	USHIDA 81	EMUL	FNAL

[185] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID	TECN	COMMENT
<2.2	90	ASRATYAN 81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.4	90	MCFARLAND 95	CCFR	FNAL
<6.5	90	BOFILL 87	CNTR	FNAL
<7.4	90	TAYLOR 83	HLBC	15-ft FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.4 \times 10^{-2}$	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.15	90	BOFILL	87	CNTR	FNAL
$<8.8 \times 10^{-2}$	90	TAYLOR	83	HLBC	15-ft FNAL

—— $\nu_\mu(\overline{\nu}_\mu) \to \nu_\tau(\overline{\nu}_\tau)$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[186] GRUWE	93	CHM2	CERN SPS

[186] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8	90	[187] GRUWE	93	CHM2	CERN SPS

[187] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

—— $\nu_e \to (\overline{\nu}_e)_L$ ——

This is a limit on lepton family-number violation and total lepton-number violation. $(\overline{\nu}_e)_L$ denotes a hypothetical left-handed $\overline{\nu}_e$. The bound is quoted in terms of $\Delta\ (m^2)$, $\sin(2\theta)$, and α, where α denotes the fractional admixture of $(V{+}A)$ charged current.

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	90	[188] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7	90	[189] COOPER	82	HLBC	BEBC CERN SPS

[188] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$.

[189] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.032	90	[190] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[191] COOPER	82	HLBC	BEBC CERN SPS

[190] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$.

[191] COOPER 82 states that existing bounds on V+A currents require α to be small.

—— $\nu_\mu \to (\overline{\nu}_e)_L$ ——

See note above for $\nu_e \to (\overline{\nu}_e)_L$ limit

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	[192] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.7	90	[193] COOPER	82	HLBC	BEBC CERN SPS

[192] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$ is almost a factor of 100 less sensitive.

[193] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	[194] COOPER	82	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90	[195] FREEDMAN	93	CNTR	LAMPF

[194] COOPER 82 states that existing bounds on V+A currents require α to be small.

[195] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$

(I) Disappearance experiments with accelerator & radioactive source neutrinos

—— $\nu_e \not\to \nu_e$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.17	90	[196] BAHCALL	95	THEO	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<40	90	[197] BORISOV	96	CNTR	IHEP-JINR detector
<14.9	90	BRUCKER	86	HLBC	15-ft FNAL
< 8	90	BAKER	81	HLBC	15-ft FNAL
<56	90	DEDEN	81	HLBC	BEBC CERN SPS
<10	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<2.3 OR >8	90	NEMETHY	81B	CNTR	LAMPF

[196] BAHCALL 95 analyzed the GALLEX ^{51}Cr calibration source experiment (ANSELMANN 95). They also gave a 95% CL limit of < 0.19 eV^2.

[197] BORISOV 96 exclusion curve extrapolated to obtain this value; however, it does not have the right curvature in this region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-2}$	90	[198] ERRIQUEZ	81	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.115	90	[199] BORISOV	96	CNTR	$\Delta(m^2) = 175$ eV^2
<0.38	90	[200] BAHCALL	95	THEO	^{51}Cr source
<0.54	90	BRUCKER	86	HLBC	15-ft FNAL
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<0.3	90	[198] DEDEN	81	HLBC	BEBC CERN SPS

[198] Obtained from a Gaussian centered in the unphysical region.

[199] BORISOV 96 sets less stringent limits at large $\Delta(m^2)$, but exclusion curve does not have clear asymptotic behavior.

[200] BAHCALL 95 analyzed the GALLEX ^{51}Cr calibration source experiment (ANSELMANN 95). They also gave a 95% CL limit of < 0.45.

—— $\nu_\mu \not\to \nu_\mu$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

These experiments also allow sufficiently large $\Delta(m^2)$.

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.23 OR >1500 OUR LIMIT					
<0.23 OR >100	90	DYDAK	84	CNTR	
<13 OR >1500	90	STOCKDALE	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29 OR >22	90	BERGSMA	88	CHRM	
<7	90	BELIKOV	85	CNTR	Serpukhov
<8.0 OR >1250	90	STOCKDALE	85	CNTR	
<0.29 OR >22	90	BERGSMA	84	CHRM	
<8.0	90	BELIKOV	83	CNTR	

$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[201] STOCKDALE	85	CNTR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[202] BERGSMA	88	CHRM	
<0.07	90	[203] BELIKOV	85	CNTR	Serpukhov
<0.27	90	[202] BERGSMA	84	CHRM	CERN PS
<0.1	90	[204] DYDAK	84	CNTR	CERN PS
<0.02	90	[205] STOCKDALE	84	CNTR	FNAL
<0.1	90	[206] BELIKOV	83	CNTR	Serpukhov

[201] This bound applies for $\Delta(m^2) = 100$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $8 < \Delta(m^2)\ <1250$ eV^2.

[202] This bound applies for $\Delta(m^2) = 0.7$–$9.$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.28 < \Delta(m^2)\ <22$ eV^2.

[203] This bound applies for a wide range of $\Delta(m^2)\ >7$ eV^2. For some values of $\Delta(m^2)$, the value is less stringent; the least restrictive, nontrivial bound occurs approximately at $\Delta(m^2) = 300$ eV^2 where $\sin^2(2\theta) <0.13$ at CL = 90%.

[204] This bound applies for $\Delta(m^2) = 1.$–$10.$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.23 < \Delta(m^2)\ <90$ eV^2.

[205] This bound applies for $\Delta(m^2) = 110$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $13 < \Delta(m^2)\ <1500$ eV^2.

[206] Bound holds for $\Delta(m^2) = 20$–1000 eV^2.

—— $\overline{\nu}_\mu \not\to \overline{\nu}_\mu$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
<7 OR >1200 OUR LIMIT				
<7 OR >1200	90	STOCKDALE	85	CNTR

$\sin^2(2\theta)$ for 190 eV^2 $<$ $\Delta(m^2)$ $<$ 320 eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[207] STOCKDALE	85	CNTR	FNAL

[207] This bound applies for $\Delta(m^2)$ between 190 and 320 or = 530 eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $7 < \Delta(m^2)\ <1200$ eV^2.

REFERENCES FOR Searches for Massive Neutrinos and Lepton Mixing

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ABREU 97I ZPHY C74 57 +Adam, Adye, Ajinenko, Alekseev+ (DELPHI Collab.)
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ACCIARRI 97P PL B412 189 +Adriani, Aguilar-Benitez, Ahlen+ (L3 Collab.)
ALLISON 97 PL B391 491 +Alner, Ayres, Barrett+ (Soudan 2 Collab.)
ALSTON-... 97 PR C55 474 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM, INEL)
BARABASH 97 ZPHY A357 351 +Gurriaran, Hubert, Hubert, Umatov (ITEP, BCEN)
BAUDIS 97 PL B407 219 L. Baudis+ (MPIH, KIAE, SASSO)
CLARK 97 PRL 79 345 +Becker-Szendy, Bratton, Brealt+ (IMB Collab.)
DESILVA 97 PR C56 2451 De Silva, Moe, Nelson, Vient (UCI)
GUENTHER 97 PR D55 54 +Hellmig+ (MPIH, KIAE, SASSO)
ROMOSAN 97 PRL 78 2912 +Arroyo, de Barbaro, de Barbaro+ (CCFR Collab.)
ACCIARRI 96G PL B377 304 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ALESSAND... 96B NPBPS 48 238 Alessandrello, Brofferio, Bucci+ (MILA, SASSO)
ALEXANDER 96P PL B385 433 +Allison, Altekamp, Ametewee+ (OPAL Collab.)
ARNOLD 96 ZPHY C72 239 R. Arnold+ (BCEN, CAEN, JINR+)
ATHANASSO... 96 PR C54 2685 Athanassopoulos, Auerbach, Burman+ (LSND Collab.)
ATHANASSO... 96B PRL 77 3082 Athanassopoulos, Auerbach, Burman+ (LSND Collab.)
BALYSH 96 PRL 77 5186 +De Silva, Lebedev, Lou, Moe+ (KIAE, UCI, CIT)
BORISOV 96 PL B369 39 +Chernichenko, Chukin, Goryachev+ (SERP, JINR)
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ARMBRUSTER 95 PL B348 19 +Blair, Bodmann, Booth+ (KARMEN Collab.)
ARNOLD 95 JETPL 61 170 +Caurier, Guyonnet, Linck+ (NEMO Collab.)
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ATHANASSO... 95 PRL 75 2650 Athanassopoulos, Auerbach+ (LSND Collab.)
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GARCIA 95 PR D51 1458 +Morales, Morales, Sarsa+ (ZARA, SCUC, PNL)
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HIDDEMANN 95 JP G21 639 +Daniel, Schwentker (MUNT)
HILL 95 PRL 75 2654 (PENN)
KOBAYASHI 95 NP A586 457 +Kobayashi (KEK, SAGA)
MCFARLAND 95 PRL 75 3993 +Naples, Arroyo, Auchinchloss+ (CCFR Collab.)
VILAIN 95C PL B351 387 +Wilquet, Petrak+ (CHARM II Collab.)
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VYRODOV 95 JETPL 61 163 +Kozlov, Martem'yanov, Machulin+ (KIAE, LAPP, CDEF)
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WIETFELDT 95 PR C52 1028 +Norman+ (LBL, UCB, SPAUL, IND, TENN)
ABDURASHI... 94 PL B328 234 Abdurashitov, Faizov, Gavrin, Gusev+ (SAGE Collab.)
ALESSAND... 94 PL B335 519 Alessandrello, Brofferio, ..., Fiorini+ (MILA)
BALYSH 94 PL B322 176 +Beck, Belyaev, Bensch+ (MPIH, KIAE, SASSO)
BECK 94 PL B336 141 +Bensch, Bockholt+ (MPIH, KIAE, SASSO)
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SMIRNOV 94 PR D49 1389 +Spergel, Bahcall (IAS, ICTP, INRM, PRIN)
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ALSTON-... 93 PRL 71 831 Alston-Garnjost+ (LBL, MTHO, UNM, INEL)
ARTEMEV 93 JETPL 58 262 +Brakhman, Zeldofich, Karelin+ (ITEP, INRM)
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AVIGNONE 91 PL B256 559 +Brodzinski, Guerard+ (SCUC, PNL, ITEP, YERE)
BELLOTTI 91 PL B266 193 +Cremonesi, Fiorini, Gervasio+ (MILA, INFN)
CASPER 91 PRL 66 2561 +Becker-Szendy, Bratton, Cady+ (IMB Collab.)
DELEENER-... 91 PR D43 3611 De Leener-Rosier, Deutsch+ (LOUV, ZURI, LAUS)
EJIRI 91 PL B258 17 +Fushimi, Kamada, Kinoshita+ (OSAK)
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KUVSHINN... 91 JETPL 54 253 A.A. Kuvshinnikov+ (KIAE)
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YOU 91 PL B265 53 +Zhu, Lu+ (BHEP, CAST+)
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AKRAWY 90L PL B247 448 +Alexander, Allison, Allport+ (OPAL Collab.)
BATUSOV 90B ZPHY C48 209 +Bunyatov, Kuznetsov, Pozharova+ (JINR, ITEP, SERP)
BERGER 90B PL B245 305 +Froehlich, Moench, Nisius+ (FREJUS Collab.)
BURCHAT 90 PR D41 3542 +King, Abrams, Adolphsen+ (Mark II Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
HIRATA 90 PRL 65 1297 +Inoue, Kajita+ (Kamiokande II Collab.)
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Translated from ZETFP 51 75.
MILEY 90 PRL 65 3092 +Avignone, Brodzinski, Collar, Reeves (SCUC, PNL)
STAUDT 90 EPL 13 31 +Muto, Klapdor-Kleingrothaus (MPIH)
VASENKO 90 MPL A5 1299 +Kirpichnikov, Kuznetsov, Starostin (ITEP, YERE)
VIDYAKIN 90 JETP 71 424 +Vyrodov, Gurevich, Koslov+ (KIAE)
Translated from ZETF 98 764.
ABRAMS 89C PRL 63 2447 +Adolphsen, Averill, Ballam+ (Mark II Collab.)
AGLIETTA 89 EPL 8 611 +Battistoni, Bellotti+ (FREJUS Collab.)
BAHCALL 89 Neutrino Astrophysics, Cambridge Univ. Press (IAS)
BLUMENFELD 89 PRL 62 2237 +Chi, Chichura, Chien+ (COLU, ILL, JHU)
DAVIS 89 ARNPS 39 467 +Mann, Wolfenstein (BNL, PENN, CMU)
ENQVIST 89 NP B317 647 +Kainulainen, Maalampi (HELS)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
MUTO 89 ZPHY A334 187 +Bender, Klapdor (TINT, MPIH)
OYAMA 89 PR D39 1481 +Hirata, Kajita, Kifune+ (Kamiokande II Collab.)
SHAW 89 PRL 63 1342 +Blanis, Bodek, Budd+ (AMY Collab.)
AFONIN 88 JETP 67 213 +Ketov, Kopeikin, Mikaelyan+ (KIAE)
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AKERLOF 88 PR D37 577 +Chapman, Errede, Ken+ (HRS Collab.)
AMMOSOV 88 ZPHY C40 487 +Belikov+ (SKAT Collab.)
BERGSMA 88 ZPHY C40 171 +Dorenbosch, Nieuwenhuis+ (CHARM Collab.)
BERNARDI 88 PL B203 332 +Carugno, Chauveau+ (PARIN, CERN, INFN, ATEN)
BIONTA 88 PR D38 768 +Blewitt, Bratton, Casper+ (IMB Collab.)
CALDWELL 88 PRL 61 510 +Eisberg, Grumm, Witherell+ (UCSB, UCB, LBL)
DURKIN 88 PRL 61 1811 +Harper, Ling+ (OSU, ANL, CIT, LBL, LSU, LANL)
ENGEL 88 PR C37 731 +Vogel, Zimbene
LOVERRE 88 PL B206 711 (INFN)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
AFONIN 87 JETPL 45 257 +Bogatov, Vershinskii+ (KIAE)
Translated from ZETFP 45 201.
AHLEN 87 PL B195 603 +Avignone, Brodzinski+ (BOST, SCUC, HARV, CHIC)
AHRENS 87 PR D36 702 + (BNL, BROW, UCI, HIRO, KEK, OSAK, PENN, STON)
BELLOTTI 87 EPL 3 889 +Cattadori, Cremonesi, Fiorini+ (MILA)
BOEHM 87 Massive Neutrinos +Vogel (CIT)
Cambridge Univ. Press, Cambridge
BOFILL 87 PR D36 3309 +Busza, Eldridge+ (MIT, FNAL, MSU)
DAUM 87 PR D36 2624 +Kettle, Jost+ (SIN, VIRG)
GRIEST 87 NP B283 681 +Seckel (UCSC, CERN)
Also 88 NP B296 1034 erratum Griest, Seckel (UCSC, CERN)
LOSECCO 87 PL B184 305 +Bionta, Blewitt, Bratton+ (IMB Collab.)
MISHRA 87 PRL 59 1397 +Auchincloss+ (COLU, CIT, FNAL, CHIC, ROCH)
OBERAUER 87 PL B198 113 +von Feilitzsch, Mossbauer (MUNT)
TALEBZADEH 87 NP B291 503 +Guy, Venus+ (BEBC WA66 Collab.)
TOMODA 87 PL B199 475 +Faessler (TUBIN)
VIDYAKIN 87 JETP 66 243 +Vyrodov, Gurevich, Kozlov+ (KIAE)
Translated from ZETF 93 424.
WENDT 87 PRL 58 1810 +Abrams, Amidei, Baden+ (Mark II Collab.)
ABRAMOWICZ 86 PRL 57 298 H. Abramowicz+ (CDHS Collab.)
AFONIN 86 JETPL 44 142 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 44 111.
ALLABY 86 PL B177 446 J.V. Allaby+ (CHARM Collab.)
ANGELINI 86 PL B179 307 +Apostolakis, Baldini+ (PISA, ATHU, PADO, WISC)
AZUELOS 86 PRL 56 2241 +Britton, Bryman+ (TRIU, CNRC)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BERNARDI 86 PL 166B 479 +Carugno+ (CURIN, INFN, CDEF, ATEN, CERN)
BERNARDI 86B PL B181 173 +Carugno+ (CURIN, INFN, CDEF, ATEN, CERN)
BORGE 86 PS 34 591 +DeRujula, Hansen, Jonson+ (ISOLDE Collab.)
BRUCKER 86 PR D34 2183 +Jacques, Kalelkar, Koller+ (RUTG, BNL, COLU)
DELEENER-... 86 PL B177 228 DeLeener-Rosier, Deutsch+ (LOUV, ZURI, LAUS)
DORENBOS... 86 PL 166B 473 Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
USHIDA 86C PRL 57 2897 +Kondo, Tasaka, Park, Song+ (FNAL E531 Collab.)
ZACEK 86 PR D34 2621 +Feilitzsch+ (CIT-SIN-TUM Collab.)
AFONIN 85 JETPL 41 435 +Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 41 355.
Also 85B JETPL 42 285 Afonin, Bogatov, Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 42 230.
AHRENS 85 PR D31 2732 +Aronson+ (BNL, BROW, KEK, OSAK, PENN+)
ALBRECHT 85I PL 163B 404 +Binder, Drescher, Schubert+ (ARGUS Collab.)
ALTZITZOG... 85 PRL 55 799 Altzitzoglou, Calaprice, Dewey+ (PRIN)
APALIKOV 85 JETPL 42 289 +Boris, Golutvin, Laptin, Lubimov+ (ITEP)
Translated from ZETFP 42 233.
BELIKOV 85 SJNP 41 589 +Volkov, Kochetkov, Mukhin+ (SERP)
Translated from YAF 41 919.
COOPER-... 85 PL 160B 207 Cooper-Sarkar+ (CERN, LOIC, OXF, SACL+)
COWSIK 85 PL 151B 62 (TATA)
DATAR 85 Nature 318 547 +Baba, Bhattacherjee, Bhuinya, Roy (BHAB, TATA)
MARKEY 85 PR C32 2215 +Boehm (CIT)
OHI 85 PL 160B 322 +Nakajima, Tamura+ (TOKY, INUS, KEK)
SIMPSON 85 PRL 54 1891 (GUEL)
STOCKDALE 85 ZPHY C27 53 +Bodek+ (ROCH, CHIC, COLU, FNAL)
ZACEK 85 PL 164B 193 +Zacek, Boehm+ (MUNI, CIT, SIN)
BALLAGH 84 PR D30 2271 +Bingham+ (UCB, LBL, FNAL, HAWA, WASH, WISC)
BERGSMA 84 PL 142B 103 +Dorenbosch, Allaby, Abt+ (CHARM Collab.)
CAVAIGNAC 84 PL 148B 387 +Hoummada, Koang+ (ISNG, LAPP)
DYDAK 84 PL 134B 281 +Feldman+ (CERN, DORT, HEIDH, SACL, WARS)
FREESE 84 NP B233 167 +Schramm (CHIC, FNAL)
GABATHULER 84 PL 138B 449 +Boehm+ (CIT, SIN, MUNI)
HAXTON 84 PPNP 12 409 +Stevenson
MINEHART 84 PRL 52 804 +Ziock, Marshall, Stephens, Daum+ (VIRG, SIN)
SCHRAMM 84 PL 141B 337 +Steigman (FNAL, BART)
STOCKDALE 84 PRL 52 1384 +Bodek+ (ROCH, CHIC, COLU, FNAL)
AFONIN 83 JETPL 38 436 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 38 361.

BELENKII 83 JETPL 38 493 +Dobrynin, Zemlyakov, Mikaelyan+ (KIAE)
Translated from ZETFP 38 406.
BELIKOV 83 JETPL 38 661 +Volkov, Kochetkov, Mukhin, Sviridov+ (SERP)
Translated from ZETFP 38 547.
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
BERGSMA 83B PL 128B 361 +Dorenbosch+ (CHARM Collab.)
BRYMAN 83B PRL 50 1546 +Dubois, Numao, Olaniya, Olin+ (TRIU, CNRC)
Also 83 PRL 50 7 Bryman, Dubois, Numao, Olaniya+ (TRIU, CNRC)
DEUTSCH 83 PR D27 1644 +Lebrun, Prieels (LOUV)
GRONAU 83 PR D28 2762 (HAIF)
KIRSTEN 83 PRL 50 474 +Richter, Jessberger (MPIH)
Also 83B ZPHY 16 189 Kirsten, Richter, Jessberger (MPIH)
SCHRECK... 83 PL 129B 265 Schreckenbach, Colvin+ (ISNG, ILLG)
TAYLOR 83 PR D28 2705 +Cence, Harris, Jones+ (HAWA, LBL, FNAL)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
HAYANO 82 PRL 49 1305 +Taniguchi, Yamanaka+ (TOKY, KEK, TSUK)
OLIVE 82 PR D25 213 +Turner (CHIC, UCSB)
VUILLEUMIER 82 PL 114B 298 +Boehm, Egger+ (CIT, SIN, MUNI)
ABELA 81 PL 105B 263 +Daum, Eaton, Frosch, Jost, Kettle, Steiner (SIN)
ARMENISE 81 PL 100B 182 +Fogli-Muciaccia+ (BARI, CERN, MILA, LALO)
ASANO 81 PL 104B 84 +Hayano, Kikutani, Kurokawa+(KEK, TOKY, INUS, OSAK)
Also 81 PR D24 1232 Shrock (STON)
ASRATYAN 81 PL 105B 301 +Efremenko, Fedotov+ (ITEP, FNAL, SERP, MICH)
BAKER 81 PRL 47 1576 +Connolly, Kahn, Kirk, Murtagh+ (BNL, COLU)
Also 78 PRL 40 144 Cnops, Connolly, Kahn, Kirk+ (BNL, COLU)
BERNSTEIN 81 PL 101B 39 +Feinberg (STEV, COLU)
BOLIEV 81 SJNP 34 787 +Butkevich, Zakidyshev, Makoev+ (INRM)
Translated from YAF 34 1418.
CALAPRICE 81 PL 106B 175 +Schreiber, Schneider+ (PRIN, IND)
DEDEN 81 PL 98B 310 +Grassler, Boeckmann, Mermikides+ (BEBC Collab.)
ERRIQUEZ 81 PL 102B 73 +Natali+ (BARI, BIRM, BRUX, EPOL, RHEL, SACL+)
KWON 81 PR D24 1097 +Boehm, Hahn, Henrikson+ (CIT, ISNG, MUNI)
NEMETHY 81B PR D23 262 + (YALE, LBL, LASL, MIT, SACL, SIN, CNRC, BERN)
SHROCK 81 PR D24 1232 (STON)
SHROCK 81B PR D24 1275 (STON)
SILVERMAN 81 PRL 46 467 +Soni (UCI, UCLA)
SIMPSON 81B PR D24 2971 (GUEL)
USHIDA 81 PRL 47 1694 + (AICH, FNAL, KOBE, SEOU, MCGI, NAGO, OSU+)
AVIGNONE 80 PR C22 594 +Greenwood (SCUC)
BOEHM 80 PL 97B 310 +Cavaignac, Feilitzsch+ (ILLG, CIT, ISNG, MUNI)
FRITZE 80 PL 96B 427 (AACH3, BONN, CERN, LOIC, OXF, SACL)
REINES 80 PRL 45 1307 +Sobel, Pasierb (UCI)
Also 59 PR 113 273 Reines, Cowan (LASL)
Also 66 PR 142 852 Nezrick, Reines (CASE)
Also 76 PRL 37 315 Reines, Gurr, Sobel (UCI)
SHROCK 80 PL 96B 159 (STON)
DAVIS 79 PR C19 2259 +Vogel, Mann, Schenter (CIT)
BLIETSCHAU 78 NP B133 205 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
CROUCH 78 PR D18 2239 +Landecker, Lathrop, Reines+ (CASE, UCI, WITW)
MEYER 77 PL 70B 469 +Nguyen, Abrams+ (SLAC, LBL, NWES, HAWA)
VYSOTSKY 77 JETPL 26 188 +Dolgov, Zeldovich (ITEP)
Translated from ZETFP 26 200.
BELLOTTI 76 LNC 17 553 +Cavalli, Fiorini, Rollier (MILA)
SZALAY 76 AA 49 437 +Marx (EOTV)
SZALAY 74 APAH 35 8 +Marx (EOTV)
COWSIK 72 PRL 29 669 +McClelland (UCB)
MARX 72 Nu Conf. Budapest +Szalay (EOTV)
GERSHTEIN 66 JETPL 4 120 +Zeldovich (KIAM)
Translated from ZETFP 4 189.

QUARKS

Notes in the Quark Listings

independent of the renormalization scheme used. It is known that the on-shell quark propagator has no infrared divergences in perturbation theory [1], so this provides a perturbative definition of the quark mass. The pole mass cannot be used to arbitrarily high accuracy because of nonperturbative infrared effects in QCD. The full quark propagator has no pole because the quarks are confined, so that the pole mass cannot be defined outside of perturbation theory.

The $\overline{\mathrm{MS}}$ running mass $\overline{m}(\mu)$ is defined by regulating the QCD theory using dimensional regularization, and subtracting the divergences using the modified minimal subtraction scheme. The $\overline{\mathrm{MS}}$ scheme is particularly convenient for Feynman diagram computations, and is the most commonly used subtraction scheme.

The Georgi-Politzer mass $\widehat{m}$ is defined using the momentum space subtraction scheme at the spacelike point $-p^2 = \widehat{m}^2$ [2]. A generalization of the Georgi-Politzer mass that is often used in computations involving QCD sum rules [3] is $\widehat{m}(\xi)$, defined at the subtraction point $p^2 = -(\xi+1)m_P^2$. QCD sum rules are discussed in more detail in the next section on light quark masses.

Lattice gauge theory calculations can be used to obtain heavy quark masses from ψ and Υ spectroscopy. The quark masses are obtained by comparing a nonperturbative computation of the meson spectrum with the experimental data. The lattice quark mass values can then be converted into quark mass values in the continuum QCD Lagrangian Eq. (1) using lattice perturbation theory at a scale given by the inverse lattice spacing. A recent computation determines the b-quark pole mass to be 5.0 ± 0.2 GeV, and the $\overline{\mathrm{MS}}$ mass to be 4.0 ± 0.1 GeV [4].

Potential model calculations of the hadron spectrum also involve the heavy quark mass. There is no way to relate the quark mass as defined in a potential model to the quark mass parameter of the QCD Lagrangian, or to the pole mass. Even in the heavy quark limit, the two masses can differ by nonperturbative effects of order Λ_{QCD}. There is also no reason why the potential model quark mass should be independent of the particular form of the potential used.

Recent work on the heavy quark effective theory [5–9] has provided a definition of the quark mass for a heavy quark that is valid when one includes nonperturbative effects and will be called the HQET mass m_Q. The HQET mass is particularly useful in the analysis of the $1/m_Q$ corrections in HQET. The HQET mass agrees with the pole mass to all orders in perturbation theory when only one quark flavor is present, but differs from the pole mass at order α_s^2 when there are additional flavors [10]. Physical quantities such as hadron masses can in principle be computed in the heavy quark effective theory in terms of the HQET mass m_Q. The computations cannot be done analytically in practice because of nonperturbative effects in QCD, which also prevent a direct extraction of the quark masses from the original QCD Lagrangian, Eq. (1). Nevertheless, for heavy quarks, it is possible to parametrize the nonperturbative effects to a given order in the $1/m_Q$ expansion in terms of a few unknown constants that can be obtained from experiment. For example, the B and D meson masses in the heavy quark effective theory are given in terms of a single nonperturbative parameter $\overline{\Lambda}$,

$$\begin{aligned} M(B) &= m_b + \overline{\Lambda} + \mathcal{O}\left(\frac{\overline{\Lambda}^2}{m_b}\right) , \\ M(D) &= m_c + \overline{\Lambda} + \mathcal{O}\left(\frac{\overline{\Lambda}^2}{m_c}\right) . \end{aligned} \tag{2}$$

This allows one to determine the mass difference $m_b - m_c = M(B) - M(D) = 3.4$ GeV up to corrections of order $\overline{\Lambda}^2/m_b - \overline{\Lambda}^2/m_c$. The extraction of the individual quark masses m_b and m_c requires some knowledge of $\overline{\Lambda}$. An estimate of $\overline{\Lambda}$ using QCD sum rules gives $\overline{\Lambda} = 0.57 \pm 0.07$ GeV [11]. The HQET masses with this value of $\overline{\Lambda}$ are $m_b = 4.74 \pm 0.14$ GeV and $m_c = 1.4 \pm 0.2$ GeV, where the spin averaged meson masses $(3M(B^*) + M(B))/4$ and $(3M(D^*) + M(D))/4$ have been used to eliminate the spin-dependent $\mathcal{O}(\overline{\Lambda}^2/m_Q)$ correction terms. The errors reflect the uncertainty in $\overline{\Lambda}$ and the unknown spin-averaged $\mathcal{O}(\overline{\Lambda}^2/m_Q)$ correction. The errors do not include any theoretical uncertainty in the QCD sum rules, which could be large. A quark model estimate suggests that $\overline{\Lambda}$ is the constituent quark mass (≈ 350 MeV), which differs significantly from the sum rule estimate. In HQET, the $1/m_Q$ corrections to heavy meson decay form-factors are also given in terms of $\overline{\Lambda}$. Thus an accurate enough measurement of these form-factors could be used to extract $\overline{\Lambda}$ directly from experiment, which then determines the quark masses up to corrections of order $1/m_Q$.

The quark mass m_Q of HQET can be related to other quark mass parameters using QCD perturbation theory at the scale m_Q. The relation between m_Q and $\widehat{m}(\xi)$ at one loop is [12]

$$m_Q = \widehat{m}(\xi)\left[1 + \frac{\widehat{\alpha}_s(\xi)}{\pi}\frac{\xi+2}{\xi+1}\log(\xi+2)\right] , \tag{3}$$

where $\widehat{\alpha}_s(\xi)$ is the strong interaction coupling constant in the momentum space subtraction scheme. The relation between m_Q and the $\overline{\mathrm{MS}}$ mass $\overline{m}$ is known to two loops [13],

$$\begin{aligned} m_Q = \overline{m}(m_Q)\Bigg[1 &+ \frac{4\overline{\alpha}_s(m_Q)}{3\pi} \\ &+ \left(16.11 - 1.04\sum_k\left(1 - \frac{m_{Q_k}}{m_Q}\right)\right)\left(\frac{\overline{\alpha}_s(m_Q)}{\pi}\right)^2\Bigg] , \end{aligned} \tag{4}$$

where $\overline{\alpha}_s(\mu)$ is the strong interaction coupling constants in the $\overline{\mathrm{MS}}$ scheme, and the sum on k extends over all flavors Q_k lighter than Q. For the b-quark, Eq. (4) reads

$$m_b = \overline{m}_b(m_b)\left[1 + 0.09 + 0.06\right] , \tag{5}$$

where the contributions from the different orders in α_s are shown explicitly. The two loop correction is comparable in size and has the same sign as the one loop term. There is presumably an error of order 0.05 in the relation between m_b and $\overline{m}_b(m_b)$ from the uncalculated higher order terms.

D. Light quarks

For light quarks, one can use the techniques of chiral perturbation theory to extract quark mass ratios. The light quark part of the QCD Lagrangian Eq. (1) has a chiral symmetry in the limit that the light quark masses are set to zero, under which left- and right-handed quarks transform independently. The mass term explicitly breaks the chiral symmetry, since it couples the left- and right-handed quarks to each other. A systematic analysis of this explicit chiral symmetry breaking provides some information on the light quark masses.

It is convenient to think of the three light quarks u, d and s as a three component column vector Ψ, and to write the mass term for the light quarks as

$$\overline{\Psi} M \Psi = \overline{\Psi}_L M \Psi_R + \overline{\Psi}_R M \Psi_L, \tag{6}$$

where M is the quark mass matrix M,

$$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}. \tag{7}$$

The mass term $\overline{\Psi} M \Psi$ is the only term in the QCD Lagrangian that mixes left- and right-handed quarks. In the limit that $M \to 0$, there is an independent SU(3) flavor symmetry for the left- and right-handed quarks. This $G_\chi = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ chiral symmetry of the QCD Lagrangian is spontaneously broken, which leads to eight massless Goldstone bosons, the π's, K's, and η, in the limit $M \to 0$. The symmetry G_χ is only an approximate symmetry, since it is explicitly broken by the quark mass matrix M. The Goldstone bosons acquire masses which can be computed in a systematic expansion in M in terms of certain unknown nonperturbative parameters of the theory. For example, to first order in M one finds that [14,15]

$$\begin{aligned} m^2_{\pi^0} &= B\,(m_u + m_d)\ , \\ m^2_{\pi^\pm} &= B\,(m_u + m_d) + \Delta_{em}\ , \\ m^2_{K^0} = m^2_{\overline{K}^0} &= B\,(m_d + m_s)\ , \\ m^2_{K^\pm} &= B\,(m_u + m_s) + \Delta_{em}\ , \\ m^2_\eta &= \frac{1}{3} B\,(m_u + m_d + 4m_s)\ , \end{aligned} \tag{8}$$

with two unknown parameters B and Δ_{em}, the electromagnetic mass difference. From Eq. (8), one can determine the quark mass ratios [14]

$$\begin{aligned} \frac{m_u}{m_d} &= \frac{2m^2_{\pi^0} - m^2_{\pi^+} + m^2_{K^+} - m^2_{K^0}}{m^2_{K^0} - m^2_{K^+} + m^2_{\pi^+}} = 0.56\ , \\ \frac{m_s}{m_d} &= \frac{m^2_{K^0} + m^2_{K^+} - m^2_{\pi^+}}{m^2_{K^0} + m^2_{\pi^+} - m^2_{K^+}} = 20.1\ , \end{aligned} \tag{9}$$

to lowest order in chiral perturbation theory. The error on these numbers is the size of the second-order corrections, which are discussed at the end of this section. Chiral perturbation theory cannot determine the overall scale of the quark masses, since it uses only the symmetry properties of M, and any multiple of M has the same G_χ transformation law as M. This can be seen from Eq. (8), where all quark masses occur only in the form Bm, so that B and m cannot be determined separately.

The mass parameters in the QCD Lagrangian have a scale dependence due to radiative corrections, and are renormalization scheme dependent. Since the mass ratios extracted using chiral perturbation theory use the symmetry transformation property of M under the chiral symmetry G_χ, it is important to use a renormalization scheme for QCD that does not change this transformation law. Any quark mass independent subtraction scheme such as $\overline{\mathrm{MS}}$ is suitable. The ratios of quark masses are scale independent in such a scheme.

The absolute normalization of the quark masses can be determined by using methods that go beyond chiral perturbation theory, such as QCD sum rules [3]. Typically, one writes a sum rule for a quantity such as B in terms of a spectral integral over all states with certain quantum numbers. This spectral integral is then evaluated by assuming it is dominated by one (or two) of the lowest resonances, and using the experimentally measured resonance parameters [16]. There are many subtleties involved, which cannot be discussed here [16].

Another method for determining the absolute normalization of the quark masses, is to assume that the strange quark mass is equal to the SU(3) mass splitting in the baryon multiplets [14,16]. There is an uncertainty in this method since in the baryon octet one can use either the Σ–N or the Λ–N mass difference, which differ by about 75 MeV, to estimate the strange quark mass. But more importantly, there is no way to relate this normalization to any more fundamental definition of quark masses.

One can extend the chiral perturbation expansion Eq. (8) to second order in the quark masses M to get a more accurate determination of the quark mass ratios. There is a subtlety that arises at second order [17], because

$$M \left(M^\dagger M\right)^{-1} \det M^\dagger \tag{10}$$

transforms in the same way under G_χ as M. One can make the replacement $M \to M(\lambda) = M + \lambda M \left(M^\dagger M\right)^{-1} \det M^\dagger$ in all formulæ,

$$\begin{aligned} M(\lambda) &= \mathrm{diag}\,(m_u(\lambda)\,,\ m_d(\lambda)\,,\ m_s(\lambda)) \\ &= \mathrm{diag}\,(m_u + \lambda m_d m_s\,,\ m_d + \lambda m_u m_s\,,\ m_s + \lambda m_u m_d)\ , \end{aligned} \tag{11}$$

so it is not possible to determine λ by fitting to data. One can only determine the ratios $m_i(\lambda)/m_j(\lambda)$ using second-order chiral perturbation theory, not the desired ratios $m_i/m_j = m_i(\lambda = 0)/m_j(\lambda = 0)$.

Dimensional analysis can be used to estimate [18] that second-order corrections in chiral perturbation theory due to the strange quark mass are of order $\lambda m_s \sim 0.25$. The ambiguity due to the redefinition Eq. (11) (which corresponds to a second-order correction) can produce a sizeable uncertainty in the ratio m_u/m_d. The lowest-order value $m_u/m_d = 0.56$ gets corrections of order $\lambda m_s(m_d/m_u - m_u/m_d) \sim 30\%$, whereas m_s/m_d gets a smaller correction of order $\lambda m_s(m_u/m_d - m_u m_d/m_s^2) \sim 15\%$. A more quantitative discussion of second-order effects can be found in Refs. 17,19,20. Since the second-order terms have a single parameter ambiguity, the value of m_u/m_d is related to the value of m_s/m_d.

The ratio m_u/m_d is of great interest since there is no strong CP problem if $m_u = 0$. To determine m_u/m_d requires fixing λ in the mass redefinition Eq. (11). There has been considerable effort to determine the chiral Lagrangian parameters accurately enough to determine m_u/m_d, for example from the analysis of the decays $\psi' \to \psi + \pi^0, \eta$, the decay $\eta \to 3\pi$, using sum rules, and from the heavy meson mass spectrum [16,21–24]. A recent paper giving a critique of these estimates is Ref. 25.

Eventually, lattice gauge theory methods will be accurate enough to be able to compute meson masses directly from the QCD Lagrangian Eq. (1), and thus determine the light quark masses. For a reliable determination of quark masses, these computations will have to be done with dynamical fermions, and with a small enough lattice spacing that one can accurately compute the relation between lattice and continuum Lagrangians.

The quark masses for light quarks discussed so far are often referred to as current quark masses. Nonrelativistic quark models use constituent quark masses, which are of order 350 MeV for the u and d quarks. Constituent quark masses model the effects of dynamical chiral symmetry breaking, and are not related to the quark mass parameters m_k of the QCD Lagrangian Eq. (1). Constituent masses are only defined in the context of a particular hadronic model.

E. Numerical values and caveats

The quark masses in the particle data listings have been obtained by using the wide variety of theoretical methods outlined above. Each method involves its own set of approximations and errors. In most cases, the errors are a best guess at the size of neglected higher-order corrections. The expansion parameter for the approximations is not much smaller than unity (for example it is $m_K^2/\Lambda_\chi^2 \approx 0.25$ for the chiral expansion), so an unexpectedly large coefficient in a neglected higher-order term could significantly alter the results. It is also important to note that the quark mass values can be significantly different in the different schemes. For example, assuming that the b-quark pole mass is 5.0 GeV, and $\overline{\alpha}_s(m_b) \approx 0.22$ gives the $\overline{\rm MS}$ b-quark mass $\overline{m}_b(\mu = m_b) = 4.6$ GeV using the one-loop term in Eq. (4), and $\overline{m}_b(\mu = m_b) = 4.3$ GeV including the one-loop and two-loop terms. The heavy quark masses obtained using HQET, QCD sum rules, or lattice gauge theory are consistent with each other if they are all converted into the same scheme. When using the data listings, it is important to remember that the numerical value for a quark mass is meaningless without specifying the particular scheme in which it was obtained. All non-$\overline{\rm MS}$ quark masses have been converted to $\overline{\rm MS}$ values in the data listings using one-loop formulæ, unless an explicit two-loop conversion is given by the authors in the original article.

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u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1.5 to 5 MeV   Charge = $\frac{2}{3}\,e$ $I_z = +\frac{1}{2}$
m_u/m_d = 0.20 to 0.70

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 3 to 9 MeV   Charge = $-\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$
m_s/m_d = 17 to 25
$\overline{m} = (m_u + m_d)/2$ = 2 to 6 MeV

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 60 to 170 MeV   Charge = $-\frac{1}{3}\,e$ Strangeness = −1
$(m_s - (m_u + m_d)/2)/(m_d - m_u)$ = 34 to 51

LIGHT QUARKS (*u*, *d*, *s*)

OMITTED FROM SUMMARY TABLE

u-QUARK MASS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass- independent subtraction scheme such as $\overline{\text{MS}}$. The ratios m_u/m_d and m_s/m_d are extracted from pion and kaon masses using chiral symmetry. The estimates of *d* and *u* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.5 to 5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9±1.1	[1] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
3.0±0.7	[2] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[3] CHOI	92B	THEO	
4.3	[4] BARDUCCI	88	THEO	
3.8±1.1	[5] GASSER	82	THEO	

[1] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_u(1 GeV) = 5.3 ± 1.5 to μ = 2 GeV.
[2] For NARISON 95C, we have rescaled m_u(1 GeV) = 4 ± 1 to μ = 2 GeV.
[3] CHOI 92B argues that $m_u = 0$ is okay based on instanton contributions to the chiral coefficients. Disagrees with DONOGHUE 92 and DONOGHUE 92B.
[4] BARDUCCI 88 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_u(1 GeV) = 5.8 to μ = 2 GeV.
[5] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_u(1 GeV) = 5.1 ± 1.5 to μ = 2 GeV.

d-QUARK MASS

See the comment for the *u* quark above.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
3 to 9 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.0±1.1	[6] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
7.4±0.7	[7] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[8] ADAMI	93	THEO	
	[9] NEFKENS	92	THEO	
6.2	[10] BARDUCCI	88	THEO	
	[11] DOMINGUEZ	87	THEO	
	[12] KREMER	84	THEO	
6.6±1.9	[13] GASSER	82	THEO	

[6] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_d(1 GeV) = 9.4 ± 1.5 to μ = 2 GeV.
[7] For NARISON 95C, we have rescaled m_d(1 GeV) = 10 ± 1 to μ = 2 GeV.
[8] ADAMI 93 obtain $m_d - m_u$=3 ± 1 MeV at μ=0.5 GeV using isospin-violating effects in QCD sum rules.
[9] NEFKENS 92 results for $m_d - m_u$ are 3.1 ± 0.4 MeV from meson masses and 3.6 ± 0.4 MeV from baryon masses.
[10] BARDUCCI 88 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_d(1 GeV) = 8.4 to μ = 2 GeV.
[11] DOMINGUEZ 87 uses QCD sum rules to obtain m_u+m_d = 15.5 ± 2.0 MeV and $m_d - m_u$ = 6 ± 1.5 MeV.
[12] KREMER 84 obtain m_u+m_d=21 ± 2 MeV at Q^2 = 1 GeV^2 using SVZ values for quark condensates; they obtain m_u+m_d=35 ± 3 MeV at Q^2 = 1 GeV^2 using factorization values for quark condensates.
[13] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_d(1 GeV) = 8.9 ± 2.6 to μ = 2 GeV.

$\overline{m} = (m_u+m_d)/2$

See the comments for the *u* quark above.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2 to 6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.7±0.2	[14] EICKER	97	LATT	$\overline{\text{MS}}$ scheme
3.6±0.6	[15] GOUGH	97	LATT	$\overline{\text{MS}}$ scheme
3.4±0.4±0.3	[16] GUPTA	97	LATT	$\overline{\text{MS}}$ scheme
4.5±1.0	[17] BIJNENS	95		

[14] EICKER 97 use lattice gauge computations with two dynamical light flavors.
[15] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives 2.1 < $\overline{m}$ < 3.5 MeV at μ=2 GeV.
[16] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamic flavors at μ = 2 GeV is 2.7 ± 0.3 ± 0.3 MeV.
[17] BIJNENS 95 determines m_u+m_d (1 GeV) = 12 ± 2.5 MeV using finite energy sum rules. We have rescaled this to 2 GeV.

s-QUARK MASS

See the comment for the *u* quark above.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
60 to 170 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
152.4±14.1	[18] CHETYRKIN	97	THEO	$\overline{\text{MS}}$ scheme
≥ 89	[19] COLANGELO	97	THEO	$\overline{\text{MS}}$ scheme
140 ±20	[20] EICKER	97	LATT	$\overline{\text{MS}}$ scheme
95 ±16	[21] GOUGH	97	LATT	$\overline{\text{MS}}$ scheme
100 ±21 ±10	[22] GUPTA	97	LATT	$\overline{\text{MS}}$ scheme
127 ±11	[23] CHETYRKIN	95	THEO	$\overline{\text{MS}}$ scheme
140 ±24	[24] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
146 ±22	[25] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[26] NEFKENS	92	THEO	
144 ± 3	[27] DOMINGUEZ	91	THEO	
88	[28] BARDUCCI	88	THEO	
	[29] KREMER	84	THEO	
130 ±41	[30] GASSER	82	THEO	

[18] CHETYRKIN 97 obtains 205.5 ± 19.1 MeV at μ=1 GeV from QCD sum rules including fourth-order QCD corrections. We have rescaled the result to 2 GeV.
[19] COLANGELO 97 is QCD sum rule computation. We have rescaled m_s(1 GeV) > 120 to μ = 2 GeV.
[20] EICKER 97 use lattice gauge computations with two dynamical light flavors.
[21] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives 54 < m_s < 92 MeV at μ=2 GeV.
[22] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamical flavors at μ = 2 GeV is 68 ± 12 ± 7 MeV.
[23] CHETYRKIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_s(1 GeV) = 171 ± 15 to μ = 2 GeV.
[24] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_s(1 GeV) = 189 ± 32 to μ = 2 GeV.
[25] For NARISON 95C, we have rescaled m_s(1 GeV) = 197 ± 29 to μ = 2 GeV.
[26] NEFKENS 92 results for $m_s-(m_u+m_d)/2$ are 111 ± 10 MeV from meson masses and 163 ± 15 MeV from baryon masses.
[27] DOMINGUEZ 91 uses QCD sum rules with Λ_{QCD} = 100–200 MeV and the SVZ value for the gluon condensate. We have rescaled m_s(1 GeV) = 194 ± 9 to μ = 2 GeV.
[28] BARDUCCI 88 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_s(1 GeV) = 118 to μ = 2 GeV.
[29] KREMER 84 obtain m_u+m_s=245±10 MeV at Q^2 = 1 GeV^2 using SVZ values for quark condensates; they obtain m_u+m_s=270 ± 10 MeV at Q^2 = 1 GeV^2 using factorization values for quark condensates.
[30] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_s(1 GeV) = 175 ± 55 to μ = 2 GeV.

LIGHT QUARK MASS RATIOS

u/d MASS RATIO

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.2 to 0.7 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44	[31] GAO	97	THEO	$\overline{\text{MS}}$ scheme
0.553±0.043	[32] LEUTWYLER	96	THEO	Compilation
<0.3	[33] CHOI	92	THEO	
0.26	[34] DONOGHUE	92	THEO	
0.30 ±0.07	[35] DONOGHUE	92B	THEO	
0.66	[36] GERARD	90	THEO	
0.4 to 0.65	[37] LEUTWYLER	90B	THEO	
0.05 to 0.78	[38] MALTMAN	90	THEO	
0.0 to 0.56	[39] CHOI	89B	THEO	
0.0 to 0.8	[40] KAPLAN	86	THEO	
0.57 ±0.04	[41] GASSER	82	THEO	
0.38 ±0.13	[42] LANGACKER	79	THEO	
0.47 ±0.11	[43] LANGACKER	79B	THEO	
0.56	[44] WEINBERG	77	THEO	

[31] GAO 97 uses electromagnetic mass splittings of light mesons.

[32] LEUTWYLER 96 uses a combined fit to $\eta \rightarrow 3\pi$ and $\psi' \rightarrow J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.

[33] CHOI 92 result obtained from the decays $\psi(2S) \rightarrow J/\psi(1S)\pi$ and $\psi(2S) \rightarrow J/\psi(1S)\eta$, and a dilute instanton gas estimate of some unknown matrix elements.

[34] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.

[35] DONOGHUE 92B computes quark mass ratios using $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$, and an estimate of L_{14} using Weinberg sum rules.

[36] GERARD 90 uses large N and η-η' mixing.

[37] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.

[38] MALTMAN 90 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Uses a criterion of "maximum reasonableness" that certain coefficients which are expected to be of order one are ≤ 3.

[39] CHOI 89 uses second-order chiral perturbation theory and a dilute instanton gas estimate of second-order coefficients in the chiral lagrangian.

[40] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.

[41] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.

[42] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.

[43] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.

[44] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

s/d MASS RATIO

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
17 to 25 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.0	[45] GAO	97	THEO	$\overline{\text{MS}}$ scheme
18.9±0.8	[46] LEUTWYLER	96	THEO	Compilation
21	[47] DONOGHUE	92	THEO	
18	[48] GERARD	90	THEO	
18 to 23	[49] LEUTWYLER	90B	THEO	
15 to 26	[50] KAPLAN	86	THEO	
19.6±1.5	[51] GASSER	82	THEO	
22 ±5	[52] LANGACKER	79	THEO	
24 ±4	[53] LANGACKER	79B	THEO	
20	[54] WEINBERG	77	THEO	

[45] GAO 97 uses electromagnetic mass splittings of light mesons.

[46] LEUTWYLER 96 uses a combined fit to $\eta \rightarrow 3\pi$ and $\psi' \rightarrow J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.

[47] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.

[48] GERARD 90 uses large N and η-η' mixing.

[49] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.

[50] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.

[51] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.

[52] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.

[53] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.

[54] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

$(m_s - m)/(m_d - m_u)$ MASS RATIO

$\overline{m} \equiv (m_u + m_d)/2$

VALUE	*DOCUMENT ID*		*TECN*
34 to 51 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[55] ANISOVICH	96	THEO
36 ±5	[56] NEFKENS	92	THEO
45 ±3	[57] NEFKENS	92	THEO
38 ±9	[58] AMETLLER	84	THEO
43.5±2.2	GASSER	82	THEO
34 to 51	GASSER	81	THEO
48 ±7	MINKOWSKI	80	THEO

[55] ANISOVICH 96 find Q=22.7 ± 0.8 with $Q^2 \equiv (m_s^2 - m^2)/(m_d^2 - m_s^2)$ from $\eta \rightarrow \pi^+\pi^-\pi^0$ decay using dispersion relations and chiral perturbation theory.

[56] NEFKENS 92 result is from an analysis of meson masses, mixing, and decay.

[57] NEFKENS 92 result is from an analysis of of baryon masses.

[58] AMETLLER 84 uses $\eta \rightarrow \pi^+\pi^-\pi^0$ and ρ dominance.

LIGHT QUARKS (*u*, *d*, *s*) REFERENCES

CHETYRKIN	97	PL B404 337	K.G. Chetyrkin, D. Pirjol, K. Schilcher	
COLANGELO	97	PL B408 340	P. Colangelo+	
EICKER	97	PL B407 290	N. Eicker+	(SESAM Collab.)
GAO	97	PR D56 4115	D.-N. Gao, B.A. Li, M.-L. Yan	
GOUGH	97	PRL 79 1622	B. Gough+	
GUPTA	97	PR D55 7203	R. Gupta, T. Bhattacharya	
ANISOVICH	96	PL B375 335	A.V. Anisovich, H. Leutwyler	
LEUTWYLER	96	PL B378 313	H. Leutwyler	
BIJNENS	95	PL B348 226	+Prades, de Rafael	(NORD, BOHR, CPPM)
CHETYRKIN	95	PR D51 5090	+Dominguez, Pirjol, Schilcher	(INRM, CAPE, MANZ)
JAMIN	95	ZPHY C66 633	+Munz	(HEIDT, MUNT)
NARISON	95C	PL B358 113		(MONP)
ADAMI	93	PR D48 2304	+Drukarev, Ioffe	(CIT, ITEP, PNPI)
CHOI	92	PL B292 159		(UCSD)
CHOI	92B	NP B383 58		(UCSD)
DONOGHUE	92	PRL 69 3444	+Holstein, Wyler	(MASA, ZURI)
DONOGHUE	92B	PR D45 892	+Wyler	(MASA, ZURI, UCSBT)
NEFKENS	92	CNPP 20 221	+Miller, Slaus	(UCLA, WASH, ZAGR)
DOMINGUEZ	91	PL B253 241	+van Gend, Paver	(CAPE, TRST, INFN)
GERARD	90	MPL A5 391		(MPIM)
LEUTWYLER	90B	NP B337 108		(BERN)
MALTMAN	90	PL B234 158	+Goldman, Stephenson Jr.	(YORKC, LANL)
CHOI	89	PRL 62 849		
CHOI	89B	PR D40 890	+Kim	(CMU, JHU)
BARDUCCI	88	PR D38 238	+Casalbuoni, De Curtis+	(FIRZ, INFN, LECE, GEVA)
Also	87	PL B193 305	Barducci, Casalbuoni+	(FIRZ, INFN, LECE, GEVA)
DOMINGUEZ	87	ANP 174 372	+de Rafael	(ICTP, MARS, WIEN)
KAPLAN	86	PRL 56 2004	+Manohar	(HARV)
AMETLLER	84	PR D30 674	+Ayala, Bramon	(BARC)
KREMER	84	PL 143B 476	+Papadopoulos, Schilcher	(MANZ)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)
GASSER	81	ANP 136 62		(BERN)
MINKOWSKI	80	NP B164 25	+Zepeda	(BERN)
LANGACKER	79	PR D19 2070	+Pagels	(DESY, PRIN)
LANGACKER	79B	PR D20 2983		(PENN)
WEINBERG	77	ANYAS 38 185		(HARV)

c

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ *e*   Charm = +1

c-QUARK MASS

The *c*-quark mass is estimated from charmonium and *D* masses. It corresponds to the "running" mass m_c ($\mu = m_c$) in the $\overline{\text{MS}}$ scheme. We have converted masses in other schemes to the $\overline{\text{MS}}$ scheme using one-loop QCD pertubation theory with $\alpha_s(\mu{=}m_c) = 0.39$. The range 1.0–1.6 GeV for the $\overline{\text{MS}}$ mass corresponds to 1.2–1.9 GeV for the pole mass (see the "Note on Quark Masses").

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.1 to 1.4 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.22±0.06	[1] DOMINGUEZ	94	THEO	$\overline{\text{MS}}$ scheme
≥ 1.23	[2] LIGETI	94	THEO	$\overline{\text{MS}}$ scheme
≥ 1.25	[3] LUKE	94	THEO	$\overline{\text{MS}}$ scheme
1.23±0.04	[4] NARISON	94	THEO	$\overline{\text{MS}}$ scheme
1.31±0.03	[5] TITARD	94	THEO	$\overline{\text{MS}}$ scheme
$1.5\ ^{+0.2}_{-0.1}\ \pm 0.2$	[6] ALVAREZ	93	THEO	
1.27±0.02	[7] NARISON	89	THEO	
1.25±0.05	[8] NARISON	87	THEO	
1.27±0.05	[9] GASSER	82	THEO	

[1] DOMINGUEZ 94 uses QCD sum rules for $J/\psi(1S)$ system and finds a pole mass of 1.46 ± 0.07 GeV.

[2] LIGETI 94 computes lower bound of 1.43 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[3] LUKE 94 computes lower bound of 1.46 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[4] NARISON 94 uses spectral sum rules to two loops, and $J/\psi(1S)$ and Υ systems.

[5] TITARD 94 uses one-loop computation of the quark potential with nonperturbative gluon condensate effects to fit $J/\psi(1S)$ and Υ states.

[6] ALVAREZ 93 method is to fit the measured x_F and p_T^2 charm photoproduction distributions to the theoretical predictions of ELLIS 89C.

[7] NARISON 89 determines the Georgi-Politzer mass at $p^2 = -m^2$ to be 1.26 ± 0.02 GeV using QCD sum rules.

[8] NARISON 87 computes pole mass of 1.46 ± 0.05 GeV using QCD sum rules, with $\Lambda(\overline{\text{MS}})$ = 180 ± 80 MeV.

[9] GASSER 82 uses SVZ sum rules. The renormalization point is μ = quark mass.

c-QUARK REFERENCES

DOMINGUEZ	94	PL B333 184	+Gluckman, Paver	(CAPE, TRST, INFN)
LIGETI	94	PR D49 R4331	+Nir	(REHO)
LUKE	94	PL B321 88	+Savage	(TNTO, UCSD, CMU)
NARISON	94	PL B341 73		(CERN, MONP)
TITARD	94	PR D49 6007	+Yndurain	(MICH, MADU)
ALVAREZ	93	ZPHY C60 53	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ELLIS	89C	NP B312 551	+Nason	(FNAL, ETH)
NARISON	89	PL B216 191		(ICTP)
NARISON	87	PL B197 405		(CERN)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)

b

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= -\frac{1}{3}\ e$ Bottom $= -1$

b-QUARK MASS

The b-quark mass is estimated from bottomonium and B masses. It corresponds to the "running" mass m_b ($\mu = m_b$) in the $\overline{\text{MS}}$ scheme. We have converted masses in other schemes to the $\overline{\text{MS}}$ scheme using one-loop QCD pertubation theory with $\alpha_s(\mu{=}m_b) = 0.22$. The range 4.1–4.5 GeV for the $\overline{\text{MS}}$ mass corresponds to 4.5–4.9 GeV for the pole mass (see the "Note on Quark Masses").

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
4.1 to 4.4 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.91 ±0.67	[1] ABREU	98I	DLPH	$\overline{\text{MS}}$ scheme
4.15 ±0.05 ±0.20	[2] GIMENEZ	97	LATT	$\overline{\text{MS}}$ scheme
4.13 ±0.06	[3] JAMIN	97	THEO	$\overline{\text{MS}}$ scheme
4.16 ±0.32 ±0.60	[4] RODRIGO	97	THEO	$\overline{\text{MS}}$ scheme
4.22 ±0.05	[5] NARISON	95B	THEO	$\overline{\text{MS}}$ scheme
4.415±0.006	[6] VOLOSHIN	95	THEO	$\overline{\text{MS}}$ scheme
4.0 ±0.1	[7] DAVIES	94	THEO	$\overline{\text{MS}}$ scheme
≥ 4.26	[8] LIGETI	94	THEO	$\overline{\text{MS}}$ scheme
≥ 4.2	[9] LUKE	94	THEO	$\overline{\text{MS}}$ scheme
4.23 ±0.04	[10] NARISON	94	THEO	$\overline{\text{MS}}$ scheme
4.397±0.025	[11] TITARD	94	THEO	$\overline{\text{MS}}$ scheme
4.32 ±0.05	[12] DOMINGUEZ	92	THEO	
4.24 ±0.05	[13] NARISON	89	THEO	
4.18 ±0.02	[14] REINDERS	88	THEO	
4.30 ±0.13	[15] NARISON	87	THEO	
4.25 ±0.1	[16] GASSER	82	THEO	

[1] ABREU 98I determines the $\overline{\text{MS}}$ mass $m_b = 2.67 \pm 0.25 \pm 0.34 \pm 0.27$ GeV at $\mu{=}M_Z$ from three jet heavy quark production at LEP. ABREU 98I have rescaled the result to $\mu = m_b$ using $\alpha_s{=}0.118 \pm 0.003$.

[2] GIMENEZ 97 uses lattice computations of the B-meson propagator and the B-meson binding energy $\overline{\Lambda}$ in the HQET. Their systematic (second) error for the $\overline{\text{MS}}$ mass is an estimate of the effects of higher-order corrections in the matching of the HQET operators (renormalon effects).

[3] JAMIN 97 apply the QCD moment method to the Υ system. They also find a pole mass of 4.60 ± 0.02.

[4] RODRIGO 97 determines the $\overline{\text{MS}}$ mass $m_b = 2.85 \pm 0.22 \pm 0.20 \pm 0.36$ GeV at $\mu{=}M_Z$ from three jet heavy quark production at LEP. We have rescaled the result.

[5] NARISON 95B uses finite energy sum rules to two-loop accuracy to determine a b-quark pole mass of 4.61 ± 0.05 GeV.

[6] VOLOSHIN 95 result was converted from a pole mass of 4827 ± 7 MeV using the one-loop formula. Pole mass was extracted using moments of the total cross section for $e^+e^- \rightarrow$ bhadrons.

[7] DAVIES 94 uses lattice computation of Υ spectroscopy. They also quote a value of 5.0 ± 0.2 GeV for the b-quark pole mass. The numerical computation includes quark vacuum polarization (unquenched); they find that the masses are independent of n_f to within their errors. Their error for the pole mass is larger than the error for the $\overline{\text{MS}}$ mass, because both are computed from the bare lattice quark mass, and the conversion for the pole mass is less accurate.

[8] LIGETI 94 computes lower bound of 4.66 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[9] LUKE 94 computes lower bound of 4.60 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[10] NARISON 94 uses spectral sum rules to two loops, and $J/\psi(1S)$ and Υ systems.

[11] TITARD 94 uses one-loop computation of the quark potential with nonperturbative gluon condensate effects to fit $J/\psi(1S)$ and Υ states.

[12] DOMINGUEZ 92 determines pole mass to be 4.72 ± 0.05 using next-to-leading order in $1/m$ in moment sum rule.

[13] NARISON 89 determines the Georgi-Politzer mass at $p^2{=}{-}m^2$ to be 4.23 ± 0.05 GeV using QCD sum rules.

[14] REINDERS 88 determines the Georgi-Politzer mass at $p^2 = -m^2$ to be 4.17 ± 0.02 using moments of $\overline{b}\gamma^\mu b$. This technique leads to a value for the mass of the B meson of 5.25 ± 0.15 GeV.

[15] NARISON 87 determines the pole mass to be 4.70 ± 0.14 using QCD sum rules, with $\Lambda(\overline{\text{MS}}) = 180 \pm 80$ MeV.

[16] GASSER 82 uses SVZ sum rules. The renormalization point is μ = quark mass.

$m_b - m_c$ MASS DIFFERENCE

The mass difference $m_b - m_c$ in the HQET scheme is 3.4 ± 0.2 GeV (see the "Note on Quark Masses").

VALUE (GeV)	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
≥ 3.29	[17] GROSSE	78

[17] GROSSE 78 obtain $(m_b - m_c) \geq 3.29$ GeV based on eigenvalue inequalities in potential models.

b-QUARK REFERENCES

ABREU	98I	PL B418 430	P. Abreu+	(DELPHI Collab.)
GIMENEZ	97	PL B393 124	V. Gimenez, G. Martinelli, C.T. Sachrajda	
JAMIN	97	NP B507 334	M. Jamin, A. Pich	
RODRIGO	97	PRL 79 193	G. Rodrigo, A. Santamaria, M. Bilenky	
NARISON	95B	PL B352 122		(MONP)
VOLOSHIN	95	IJMP A10 2865		(MINN)
DAVIES	94	PRL 73 2654	+Hornbostel+	(GLAS, SMU, CORN, EDIN, OSU, FSU)
LIGETI	94	PR D49 R4331	+Nir	(REHO)
LUKE	94	PL B321 88	+Savage	(TNTO, UCSD, CMU)
NARISON	94	PL B341 73		(CERN, MONP)
TITARD	94	PR D49 6007	+Yndurain	(MICH, MADU)
DOMINGUEZ	92	PL B293 197	+Paver	(CAPE, TRST, INFN)
NARISON	89	PL B216 191		(ICTP)
REINDERS	88	PR D38 947		(BONN)
NARISON	87	PL B197 405		(CERN)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)
GROSSE	78	PL 79B 103	+Martin	(CERN)

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\ e$ Top $= +1$

THE TOP QUARK

Revised April 1998 by M. Mangano (CERN) and T. Trippe (LBNL).

A. Introduction: The top quark is the $Q = 2/3$, $T_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark (see our review on the "Standard Model of Electroweak Interactions" for more information). This note collects a summary of its currently measured properties, in addition to a discussion of the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*) and some comments on of the prospects for future improvements.

B. Top quark production at the Tevatron: At the Tevatron energy, 1.8 TeV, top quarks are dominantly produced in pairs from pure QCD processes: $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$. The production cross section through these channels is expected to be approximately 5 pb at $m_t = 175$ GeV/c^2, with a dominant 90% contribution from the $q\bar{q}$ annihilation process. Smaller contributions come from the single-top production mechanisms, namely $q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}$ and $qg \rightarrow q't\bar{b}$, this last mediated by a t-channel virtual-W exchange. The combined rate from these processes is approximately 2.5 pb at $m_t = 175$ GeV (see Ref. 1 and references therein). The actual contribution of these channels to the detected final states is further reduced relative to the dominant pair-production mechanisms, due to the lower experimental acceptances.

With a mass above the Wb threshold, the top quark decay width is dominated by the two-body decay $t \rightarrow Wb$. Neglecting terms of order m_b^2/m_t^2 and of order $(\alpha_s/\pi)m_W^2/m_t^2$, this is predicted in the Standard Model to be [2]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1 - \frac{M_W^2}{m_t^2}\right)^2\left(1 + 2\frac{M_W^2}{m_t^2}\right)\left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]. \tag{1}$$

The use of G_F in this equation accounts for the largest part of the one-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width values increase with mass, going for example from 1.02 GeV at $m_t =$ 160 GeV to 1.56 GeV at $m_t =$ 180 GeV (we used $\alpha_S(\mathrm{M_Z}) =$ 0.118). With such a correspondingly short lifetime, the top quark is expected to decay before top-flavored hadrons or $t\bar{t}$-quarkonium bound states can form.

In top decay, the Ws and Wd final states are expected to be suppressed relative to Wb by the square of the CKM matrix elements V_{ts} and V_{td}, whose values can be estimated under the assumption of unitarity of the three-generation CKM matrix to be less than 0.042 and 0.013, respectively (see our review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in the current edition for more information).

Typical final states for the leading pair-production process therefore belong to three classes:

A. $t\bar{t} \to W b W \bar{b} \to q\bar{q}' b q'' \bar{q}''' \bar{b}$,

B. $t\bar{t} \to W b W \bar{b} \to q\bar{q}' b \ell \bar{\nu}_\ell \bar{b} + \bar{\ell} \nu_\ell b q \bar{q}' \bar{b}$,

C. $t\bar{t} \to W b W \bar{b} \to \bar{\ell} \nu_\ell b \ell' \bar{\nu}_{\ell'} \bar{b}$,

where A, B, and C are referred to as the all-jets, lepton + jets, and dilepton channels, respectively.

The final state quarks emit radiation and evolve into jets of hadrons. The precise number of jets reconstructed by the detectors varies event by event, as it depends on the decay kinematics, as well as on the precise definition of jet used in the analysis. The neutrinos are reconstructed via the large imbalance in detected transverse momentum of the event (missing E_T).

The observation of $t\bar{t}$ pairs has been reported in all of the above decay modes. As discussed in detail below, the top quark production and decay properties extracted from the three different decay channels above are all consistent with each other, within the present experimental sensitivity. In particular, the $t \to Wb$ decay mode has been confirmed by the reconstruction of the $W \to jj$ invariant mass in the $\ell\bar{\nu}_\ell b\bar{b}jj$ final state [3].

The extraction of the top-quark properties from the Tevatron data requires a good understanding of the production and decay mechanisms of the top itself, as well as of the large background processes. The theoretical estimates of the physics backgrounds have large uncertainties, since only leading order QCD calculations are available for most of the relevant processes (W+3 and 4 jets, or WW+2 jets). While this limitation is known to affect the estimates of the overall production rates, it is believed that the LO determination of the event kinematics and of the fraction of W plus multi-jet events containing b quarks is rather accurate. In particular, one expects the E_T spectrum of these jets to fall rather steeply, the jet direction to point preferentially at small angles from the beams, and the fraction of events with b quarks to be of the order of few percent. In the case of the top signal, *vice versa*, the b fraction is $\sim$ 100% and the jets are rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio by either requiring the presence of a b quark, or by selecting very energetic and central kinematical configurations.

A detailed study of control samples with features similar to those of the relevant backgrounds, but free from possible top contamination is required to provide a reliable check on the background estimates.

C. Measured top properties: All direct measurements of top quark production and decay have been made by the CDF and D0 experiments at the Fermilab Tevatron collider in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Since the first direct experimental evidence for the top quark in 1994 [4] by CDF (a 2.8 σ effect. See this review in our 1996 edition [5] for more details) and the conclusive observation by both CDF and D0 in 1995 [6,7], the integrated luminosity has increased to 109 pb^{-1} for CDF and 125 pb^{-1} for D0, allowing significant improvements in the measurement of the top production cross section, mass, and decay properties.

D0 and CDF determine the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$ from their numbers of top candidates, their estimated background, their $t\bar{t}$ acceptance, and their integrated luminosity, assuming Standard Model decays $t \to Wb$ with unity branching ratio. Table 1 shows the measured cross sections from D0 and CDF along with the range of theoretical expectations, evaluated at the m_t values used by the experiments in calculating their acceptances. There is fairly good agreement between the experiments and the theoretical expectations, although the CDF values are somewhat higher than the theory values. This agreement supports the hypothesis that the excess of events over background in all of these channels is due to $t\bar{t}$ production. A joint CDF/D0 working group is expected to produce a combined cross section for the two experiments in the near future.

Future precise determinations of the top production cross section will test the current theoretical understanding of the production mechanisms [8–11]. A precise understanding of top production at the Tevatron is important for the extrapolation to the higher energies of future colliders, like the LHC, where the expected large cross section will enable more extensive studies. Discrepancies in rate between theory and data, on the other hand, would be more exciting and might indicate the presence of exotic production channels, as predicted in some models. In this case, one should also expect a modification of kinematical distributions such as the invariant mass of the top pair or the top quark transverse momentum.

The top mass has been measured in the lepton + jets and dilepton channels by both D0 and CDF, and in the all-jets channel by CDF. At present, the most precise measurements come from the lepton + jets channel with four or more jets and large missing E_T. In this channel, each event is subjected to a two-constraint kinematic fit to the hypothesis $t\bar{t} \to W^+ b W^- \bar{b} \to \ell \nu_\ell q \bar{q}' b \bar{b}$, assuming that the four highest E_T jets are the $t\bar{t}$ daughters. The shape of the distribution of fitted top masses from these events is compared to templates

Table 1: Cross section for $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV from DØ ($m_t = 173.3$ GeV/c^2), CDF ($m_t = 175$ GeV/c^2), and theory.

$t\bar{t}$ cross section	Source	Ref.	Method
4.1 ± 2.0 pb	DØ	[12]	lepton + jets
8.2 ± 3.5 pb	DØ	[12]	lepton + jets/μ
6.3 ± 3.3 pb	DØ	[12]	dileptons + $e\nu$
5.5 ± 1.8 pb	DØ	[12]	Ref. 12 combined
$5.0 - 5.8$ pb	Theory	[8–11]	at $m_t = 173.3$ GeV/c^2
$6.7^{+2.0}_{-1.7}$ pb	CDF	[13]	lepton + jet
$8.2^{+4.4}_{-3.4}$ pb	CDF	[14]	dileptons
$10.1^{+4.5}_{-3.6}$ pb	CDF	[15]	all jets
$7.6^{+1.8}_{-1.5}$ pb	CDF	[13]	Refs. 13–15 combined
$4.75 - 5.5$ pb	Theory	[8–11]	at $m_t = 175$ GeV/c^2

Table 2: Top mass measurements from DØ and CDF.

m_t (GeV/c^2)	Source	Ref.	Method
$173.3 \pm 5.6 \pm 5.5$	DØ	[16]	lepton + jets
$168.4 \pm 12.3 \pm 3.6$	DØ	[17]	dileptons
$172.1 \pm 5.2 \pm 4.9$	DØ	[16]	DØ combined
$175.9 \pm 4.8 \pm 4.9$	CDF	[18]	lepton + jet
$161 \pm 17 \pm 10$	CDF	[14]	dileptons
$186 \pm 10 \pm 12$	CDF	[15]	all jets
$173.8 \pm 3.5 \pm 3.9$ *	PDG		PDG Average

* Average does not include CDF all jets. See text.

expected from a mixture of background and signal distributions for a series of assumed top masses. This comparison yields values of the likelihood as a function of top mass, from which a best value of the top mass and its error are obtained. The results are shown in Table 2. The systematic error, the second error shown, is comparable to the statistical error and is primarily due to uncertainties in the jet energy scale and the Monte Carlo modeling.

Less precise determinations of the top mass come from the dilepton channel with two or more jets and large missing $\not{E}_T$, and from the all-jets channel. In the dilepton channel a kinematically constrained fit is not possible because there are two missing neutrinos, so experiments must use other mass estimators than the reconstructed top mass. Any quantity which is correlated with top mass can be used as a mass estimator. DØ uses the fact that if m_t is assumed, the $t\bar{t}$ system can be reconstructed (up to a four-fold ambiguity). They compare the resulting kinematic configurations to expectations from $t\bar{t}$ production and obtain a weight *vs* m_t curve for each event, which they coarsely histogram to obtain four shape-sensitive quantities as their multidimensional mass estimator. Their method yields a significant increase in precision over one-dimensional estimators. CDF does two analyses, one using the b quark jet energy and the other using the $\ell\,b$-jet invariant mass. Both DØ and CDF obtain the top mass and error from these mass estimators using the same template likelihood method as for the lepton + jets channel. CDF also measures the mass in the all-jets channel using events with six or more jets, at least one of which is tagged as a b jet by the presence of a secondary vertex.

As seen in Table 2, all top mass results are in good agreement, giving further support to the hypothesis that these events are due to $t\bar{t}$ production. A joint CDF/DØ working group is expected to produce a combined CDF/DØ average top mass in the near future, taking into account correlations between the systematic errors in the different measurements. In the meantime, the PDG obtains an average top mass as follows. Using DØ's approach to combining their own results [16], we assume a 100% correlation between the DØ lepton + jets and dilepton systematic errors for jet energy scale, signal model, and multiple interactions, and 0% correlation between their other systematic errors. CDF have not published their combined results, but we can include CDF results for lepton + jets [18] and dileptons [14] by assuming 100% correlation between the signal model errors in all four results and 100% correlation between the jet energy scale errors of the two CDF results. In addition, in a given channel, lepton + jets or dileptons, we assume a 100% correlation between systematic errors in the CDF and DØ background shapes. All other correlations are assumed to be zero. We do not include the CDF all jets channel because we do not know what correlation to assume for its signal model error. These assumptions yield a PDG average top mass of $m_t = 173.8 \pm 3.5 \pm 3.9$ GeV/c^2 $= 173.8 \pm 5.2$ GeV/c^2.

Given the experimental technique used to extract the top mass, the top mass values should be taken as representing the top *pole mass* (see our review "Note on Quark Masses" in the current edition).

The extraction of the value of the top mass from the analyses described requires, in addition to an understanding of the absolute energy calibration and resolution of the detectors, also an *a priori* knowledge of the structure of the final state. Given the hardness of a $t\bar{t}$ production process, jets can in fact arise not only from the top decays, but also from the initial state gluon radiation. Furthermore, quarks from the top decays can radiate additional jets. The presence of these additional jets will affect the shape of the mass spectrum, depending on the details of how the samples used for the mass determination were defined. QCD calculations used to model top production and decay are expected to be rather reliable, but residual uncertainties remain and are accounted for in the overall systematic error on the top mass. The larger samples that will become available in the future will allow more strict selection criteria, leading to purer samples of top quarks. For example, requesting the presence of four and only four jets in the event, two of which are b tagged jets and the other two of which are central jets of high-E_T, should largely reduce the possibility of erroneously including jets not coming from the top decays into the mass reconstruction. This will significantly improve the mass resolution and will make it less sensitive to the theoretical uncertainties. With a smaller error on the top mass, and with yet improved measurements of the electroweak parameters, it will be possible to get important constraints on the value of the Higgs mass. Current global fits performed within the Standard Model and its minimal supersymmetric extension provide indications for a relatively light Higgs (see the "H^0 Indirect Mass Limits from Electroweak Analysis" in the Particle Listings of the current edition), possibly within the range of the upcoming LEP2 experiments.

Measurements of other properties of top decays are underway. CDF reports a direct measurement of the $t \to Wb$ branching ratio [19]. Their preliminary result, obtained by comparing the number of events with 0, 1 and 2 tagged b jets and using the known tagging efficiency, is: $R = \mathrm{B}(t \to Wb)/\sum_{q=d,s,b}\mathrm{B}(t \to Wq) = 0.99 \pm 0.29$ where the error includes statistical and systematic uncertainties, or as a lower limit, $R > 0.58$ at 95% CL. Assuming that non-W decays of top can be neglected, that only three generations exist, and assuming the unitarity of the CKM matrix, they extract a CKM matrix-element $|V_{tb}| = 0.99 \pm 0.15$ or $|V_{tb}| > 0.76$ at 95% CL. A more direct measurement of the Wtb coupling constant will be possible when enough data have been accumulated to detect the less frequent single-top production processes, such as $q\bar{q}' \to W^* \to t\bar{b}$ and $qb \to q't$ via W exchange. The cross-sections for these processes are proportional to $|V_{tb}|^2$, and no assumption on the number of families or the unitarity of the CKM matrix needs to be made to extract $|V_{tb}|$.

Both CDF and DØ are searching for non-Standard Model top decays, particularly those expected in supersymmetric models. CDF [20] has published a direct search for top decay to a charged Higgs and a b quark followed by $H^+ \to \tau\nu_\tau$ with τ decaying to hadrons. This search focuses on large $\tan\beta$, the ratio of the vacuum expectation values for the two Higgs doublets. As $\tan\beta$ increases, the $t \to H^+b$ and $H^+ \to \tau\nu_\tau$ branching fractions are both expected to approach one, maximizing sensitivity to this mode. CDF sees no excess of events over the expected background, giving an exclusion region in the m_{H^+} *vs* $\tan\beta$ plane (see their Fig. 3) which extends to m_{H^+} values higher than existing LEP limits for $\tan\beta$ above 100, assuming $m_t = 175$ GeV/c^2 and $\sigma_{t\bar{t}} = 5.0$ pb.

DØ and CDF are looking for top disappearance via $t \to H^+b$, $H^+ \to \tau\nu$ or $c\bar{s}$. These charged Higgs decays would not be detected in the lepton + jets or dilepton cross section analyses as efficiently as $t \to W^{\pm}b$, primarily because of the absence of energetic isolated leptons in the Higgs decays. This would give rise to measured cross sections lower than the Standard Model prediction, assuming that non-Standard Model $t\bar{t}$ production is negligible. The H^+ is expected to decay to $\tau\nu$ at high $\tan\beta$ and to $c\bar{s}$ or $Wb\bar{b}$ at low $\tan\beta$. The $\tau\nu$ and $c\bar{s}$ modes lead to disagreement with the observed cross section and thus to exclusion regions at both low and high $\tan\beta$. At high $\tan\beta$ these experiments can potentially probe m_{H^+} up to the top decay kinematic limit, while at low $\tan\beta$ the m_{H^+} reach is expected to be weakened to perhaps 140 GeV. This is because at higher m_{H^+} and low $\tan\beta$ the $H^+ \to Wb\bar{b}$ decay mode dominates [21] and cannot easily be distinguished from Standard Model top decay.

Searches for other possible new particles such as a supersymmetric scalar top quark ($\tilde{t}$) via $t \to \tilde{t}\widetilde{\chi}^0$, are under way both at CDF and DØ.

CDF reports a search for flavor changing neutral current (FCNC) decays of the top quark $t \to q\gamma$ and $t \to qZ$ [22], for which the Standard Model predicts such small rates that their observation here would indicate new physics. They assume that one top decays via FCNC while the other decays via Wb. For the $t \to q\gamma$ search, they search for two signatures, depending on whether the W decays leptonically or hadronically. For leptonic W decay, the signature is $\gamma\ell$ plus missing E_T and two or more jets, while for hadronic W decay, it is γ plus four or more jets, one with a secondary vertex b tag. They observe one event ($\mu\gamma$) with an expected background of less than half an event, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to q\gamma) < 3.2\%$ at 95% CL.

For the $t \to qZ$ FCNC search, they look for $Z \to \mu\mu$ or ee and $W \to$ hadrons, giving a Z plus four jet signature. They observe one $\mu\mu$ event with an expected background of 1.2 events, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to qZ) < 33\%$ at 95% CL. Both the γ and Z limits are non-background subtracted (i.e. conservative) estimates.

Studies of the decay angular distributions are also in progress using the current data sets. They will allow a first direct analysis of the $V - A$ nature of the Wtb coupling, as well as providing direct information on the relative coupling of longitudinal and transverse W bosons to the top. In the Standard Model, the fraction of decays to transversely polarized W bosons is expected to be $1/(1 + m_t^2/2M_W^2)$ (30% for $m_t = 175$ GeV. Deviations from this value would challenge the Higgs mechanism of spontaneous symmetry breaking.

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t-Quark Mass in $p\bar{p}$ Collisions

The *t* quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization. OUR EVALUATION is an AVERAGE which incorporates correlations as described in the note "The Top Quark"' above.

For earlier search limits see the *Review of Particle Physics*, Phys. Rev. **D54**,1 (1996).

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.8± 5.2 OUR EVALUATION				
168.4±12.3± 3.6	[1] ABBOTT	98D	D0	$\ell\ell$ + jets
173.3± 5.6± 5.5	[1] ABBOTT	98F	D0	ℓ + jets
175.9± 4.8± 4.9	[2] ABE	98E	CDF	ℓ + jets
161 ±17 ±10	[2] ABE	98F	CDF	$\ell\ell$ + jets
• • • We do not use the following data for averages, fits, limits, etc. • • •				
173.3± 5.6± 6.2	[1] ABACHI	97E	D0	ℓ + jets
186 ±10 ±12	[2,3] ABE	97R	CDF	6 or more jets
$199\ ^{+19}_{-21}\ \pm22$	ABACHI	95	D0	ℓ + jets
176 ± 8 ±10	ABE	95F	CDF	ℓ + b-jet
$174\ \pm10\ ^{+13}_{-12}$	ABE	94E	CDF	ℓ + b-jet

[1] Result is based on 125 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV.

[2] Result is based on 109 ± 7 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV.

[3] ABE 97R result is based on the first observation of all hadronic decays of $t\bar{t}$ pairs. Single b-quark tagging with jet-shape variable constraints was used to select signal enriched multi-jet events. Not used in OUR EVALUATION because of unknown correlations in the systematic errors. A joint CDF-DØ working group is considering how to include these results.

t-Quark Decay Branching Fractions

VALUE (%)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[4] ABE	97V	CDF	$\ell\tau$ + jets

[4] ABE 97V searched for $t\bar{t} \to (\ell\nu_\ell)\,(\tau\nu_\tau)b\bar{b}$ events in 109 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. They observed 4 candidate events where one expects ∼ 1 signal and ∼ 2 background events. Three of the four observed events have jets identified as b candidates.

Indirect *t*-Quark Mass from Standard Model Electroweak Fit

"OUR EVALUATION" below is from the fit to electroweak data described in the "Electroweak Model and Constraints on New Physics" section of this Review. This fit result does not include direct measurements of m_t. The central value and first uncertainty are for $M_H = M_Z$. The second uncertainty is the shift from changing M_H to 300 GeV.

The RVUE values are based on the data described in the footnotes. RVUE's published before 1994 and superseded analyses are now omitted. For more complete listings of earlier results, see the 1994 edition (Physical Review **D50** 1173 (1994)).

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
170 ± 7 (+14) OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$172.0^{+\ 5.8}_{-\ 5.7}$	[5] DEBOER	97B	RVUE	Electroweak + Direct
$157\ ^{+16}_{-12}$	[6] ELLIS	96C	RVUE	Z parameters, m_W, low energy
$175\ \pm11\ ^{+17}_{-19}$	[7] ERLER	95	RVUE	Z parameters, m_W, low energy
$180 \pm 9^{+19}_{-21} \mp 2.6 \pm 4.8$	[8] MATSUMOTO	95	RVUE	
$157\ ^{+36}_{-48}\ ^{+19}_{-20}$	[9] ABREU	94	DLPH	Z parameters
$158\ ^{+32}_{-40}\ \pm19$	[10] ACCIARRI	94	L3	Z parameters
$132\ ^{+41}_{-48}\ ^{+24}_{-18}$	[11] AKERS	94	OPAL	Z parameters
$190\ ^{+39}_{-48}\ ^{+12}_{-14}$	[12] ARROYO	94	CCFR	ν_μ iron scattering
$184\ ^{+25}_{-29}\ ^{+17}_{-18}$	[13] BUSKULIC	94	ALEP	Z parameters
153 ±15	[14] ELLIS	94B	RVUE	Electroweak
$177\ \pm\ 9\ ^{+16}_{-20}$	[15] GURTU	94	RVUE	Electroweak
$174\ ^{+11}_{-13}\ ^{+17}_{-18}$	[16] MONTAGNA	94	RVUE	Electroweak
$171\ \pm12\ ^{+15}_{-21}$	[17] NOVIKOV	94B	RVUE	Electroweak
$160\ ^{+50}_{-60}$	[18] ALITTI	92B	UA2	m_W, m_Z

[5] DEBOER 97B result is from the five-parameter fit which varies m_Z, m_t, m_H, α_s, and $\alpha(m_Z)$ under the contraints: m_t=175 ± 6 GeV, $1/\alpha(m_Z)$=128.896 ± 0.09. They found $m_H = 141^{+140}_{-\ 77}$ GeV and $\alpha_s(m_Z)$=0.1197 ± 0.0031.

[6] ELLIS 96C result is a the two-parameter fit with free m_t and m_H, yielding also $m_H = 65^{+117}_{-\ 37}$ GeV.

[7] ERLER 95 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding $\alpha_s(m_Z) = 0.127(5)(2)$.

[8] MATSUMOTO 95 result is from fit with free m_t to Z parameters, M_W, and low-energy neutral-current data. The second error is for $m_H = 300^{+700}_{-240}$ GeV, the third error is for $\alpha_s(m_Z) = 0.116 \pm 0.005$, the fourth error is for $\delta\alpha_{\text{had}} = 0.0283 \pm 0.0007$.

[9] ABREU 94 value is for $\alpha_s(m_Z)$ constrained to 0.123 ± 0.005. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[10] ACCIARRI 94 value is for $\alpha_s(m_Z)$ constrained to 0.124 ± 0.006. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[11] AKERS 94 result is from fit with free α_s. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV. The 95%CL limit is $m_t < 210$ GeV.

[12] ARROYO 94 measures the ratio of the neutral-current and charged-current deep inelastic scattering of ν_μ on an iron target. By assuming the SM electroweak correction, they obtain $1 - m_W^2/m_Z^2 = 0.2218 \pm 0.0059$, yielding the quoted m_t value. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[13] BUSKULIC 94 result is from fit with free α_s. The second error is from $m_H = 300^{+700}_{-240}$ GeV.

[14] ELLIS 94B result is fit to electroweak data available in spring 1994, including the 1994 A_{LR} data from SLD. m_t and m_H are two free parameters of the fit for $\alpha_s(m_Z) = 0.118 \pm 0.007$ yielding m_t above, and $m_H = 35^{+70}_{-22}$ GeV. ELLIS 94B also give results for fits including constraints from CDF's direct measurement of m_t and CDF's and DØ 's production cross-section measurements. Fits excluding the A_{LR} data from SLD are also given.

[15] GURTU 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.125 \pm 0.005^{+0.003}_{-0.001}$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP, M_W, νN, and SLD electroweak data available in spring 1994.

[16] MONTAGNA 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.124$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Errors in $\alpha(m_Z)$ and m_b are taken into account in the fit. Uses LEP, SLC, and M_W/M_Z data available in spring 1994.

[17] NOVIKOV 94B result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.125 \pm 0.005 \pm 0.002$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP and CDF electroweak data available in spring 1994.

[18] ALITTI 92B assume $m_H = 100$ GeV. The 95%CL limit is $m_t < 250$ GeV for $m_H <$ 1 TeV.

t-Quark REFERENCES

ABBOTT 98D PRL 80 2063 B. Abbott+ (D0 Collab.)
ABBOTT 98F PR D (to be publ.) B. Abbott+ (D0 Collab.)
FERMILAB-Pub-98/031-E
ABE 98E PRL 80 2767 F. Abe+ (CDF Collab.)
ABE 98F PRL 80 2779 F. Abe+ (CDF Collab.)
ABACHI 97E PRL 79 1197 S. Abachi+ (D0 Collab.)
ABE 97R PRL 79 1992 F. Abe+ (CDF Collab.)
ABE 97V PRL 79 3585 F. Abe+ (CDF Collab.)
DEBOER 97B ZPHY C75 627 W. de Boer, A. Dabelstein, W. Hollik+
ELLIS 96C PL B389 321 +Fogli, Lisi (CERN, BARI)
ABACHI 95 PRL 74 2632 +Abbott, Abolins, Acharya, Adam+ (D0 Collab.)
ABE 95F PRL 74 2626 +Akimoto, Akopian, Albrow, Amendolia+ (CDF Collab.)
ERLER 95 PR D52 441 +Langacker (PENN)
MATSUMOTO 95 MPL A10 2553 (KEK)
ABE 94E PR D50 2966 +Albrow, Amendolia, Amidei, Antos+ (CDF Collab.)
Also 94F PRL 73 225 Abe, Albrow, Amidei, Antos, Anway-Weise+ (CDF Collab.)
ABREU 94 NP B418 403 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 94 ZPHY C62 551 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
AKERS 94 ZPHY C61 19 +Alexander, Allison+ (OPAL Collab.)
ARROYO 94 PRL 72 3452 +King, Bachman+ (COLU, CHIC, FNAL, ROCH, WISC)
BUSKULIC 94 ZPHY C62 539 +Casper, De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
ELLIS 94B PL B333 118 +Fogli, Lisi (CERN, BARI)
GURTU 94 MPL A9 3301 (TATA)
MONTAGNA 94 PL B335 484 +Nicrosini, Passarino, Piccinini (INFN, PAVI, CERN, TORI)
NOVIKOV 94B MPL A9 2641 +Okun, Rozanov, Vysotsky (GUEL, CERN, ITEP)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
ALITTI 92B PL B276 354 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)

b' (4^{th} Generation) Quark, Searches for

MASS LIMITS for b' (4^{th} Generation) Quark or Hadron in $p\overline{p}$ Collisions

These experiments (except for MUKHOPADHYAYA 93 and ABACHI 97D) assume that no two-body modes such as $b' \rightarrow b\gamma$, $b' \rightarrow bg$, or $b' \rightarrow cH^+$ are available.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>128	95	[1] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 96	95	[2] ABACHI	97D	D0	FCNC ($b' \rightarrow b\gamma$)
> 75	95	[3] MUKHOPAD...	93	RVUE	FCNC ($b' \rightarrow b\ell^+\ell^-$)
> 85	95	[4] ABE	92	CDF	$\ell\ell$
> 72	95	[5] ABE	90B	CDF	$e + \mu$
> 54	95	[6] AKESSON	90	UA2	e + jets + missing E_T
> 43	95	[7] ALBAJAR	90B	UA1	μ + jets
> 34	95	[8] ALBAJAR	88	UA1	e or μ + jets

[1] ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W. See FROGGATT 97.

[2] ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on $B(b'\overline{b}' \rightarrow \gamma + 3\text{ jets})$ and $B(b'\overline{b}' \rightarrow 2\gamma + 2\text{ jets})$, which can be interpreted as the lower mass bound $m_{b'} > m_Z + m_b$.

[3] MUKHOPADHYAYA 93 analyze CDF dilepton data of ABE 92G in terms of a new quark decaying via flavor-changing neutral current. The above limit assumes $B(b' \rightarrow b\ell^+\ell^-)$=1%. For an exotic quark decaying only via virtual Z [$B(b\ell^+\ell^-)$ = 3%], the limit is 85 GeV.

[4] ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.

[5] ABE 90B exclude the region 28–72 GeV.

[6] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta| < 2.2$, and excluded $m_{b'}$ between 30 and 69 GeV.

[7] For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

[8] ALBAJAR 88 study events at E_{cm} = 546 and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The lower mass limit is obtained by using a conservative estimate for the $b'\overline{b}'$ production cross section and by assuming that it cannot be produced in W decays. The value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88.

MASS LIMITS for b' (4^{th} Generation) Quark or Hadron in e^+e^- Collisions

Search for hadrons containing a fourth-generation −1/3 quark denoted b'.

The last column specifies the assumption for the decay mode (CC denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>46.0	95	[9] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[10] ADRIANI	93G	L3	Quarkonium
>44.7	95	ADRIANI	93M	L3	$\Gamma(Z)$
>45	95	ABREU	91F	DLPH	$\Gamma(Z)$
none 19.4–28.2	95	ABE	90D	VNS	Any decay; event shape
>45.0	95	ABREU	90D	DLPH	$B(CC) = 1$; event shape
>44.5	95	[11] ABREU	90D	DLPH	$b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$, $\tau^-\nu$
>40.5	95	[12] ABREU	90D	DLPH	$\Gamma(Z \rightarrow \text{hadrons})$
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[13] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[13] AKRAWY	90B	OPAL	$B(CC) = 1$; acoplanarity
>46	95	[14] AKRAWY	90J	OPAL	$b' \rightarrow \gamma$ + any
>27.5	95	[15] ABE	89E	VNS	$B(CC)$ =1; μ, e
none 11.4–27.3	95	[16] ABE	89G	VNS	$B(b' \rightarrow b\gamma) > 10\%$; isolated γ
>44.7	95	[17] ABRAMS	89C	MRK2	$B(CC)$= 100%; isol. track
>42.7	95	[17] ABRAMS	89C	MRK2	$B(bg)$= 100%; event shape
>42.0	95	[17] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[18,19] ADACHI	89C	TOPZ	$B(CC)$ =1; μ
>28.8	95	[20] ENO	89	AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	[20,21] ENO	89	AMY	any decay; event shape
>29.0	95	[20] ENO	89	AMY	$B(b' \rightarrow bg) \gtrsim 85\%$; event shape
>24.4	95	[22] IGARASHI	88	AMY	μ,e
>23.8	95	[23] SAGAWA	88	AMY	event shape
>22.7	95	[24] ADEVA	86	MRKJ	μ
>21		[25] ALTHOFF	84C	TASS	R, event shape
>19		[26] ALTHOFF	84I	TASS	Aplanarity

[9] DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes $b' \rightarrow bg$ for $B(b' \rightarrow bg) > 65\%$ $b' \rightarrow b\gamma$ for $B(b' \rightarrow b\gamma) > 5\%$ are excluded. Charged Higgs decay were not discussed.

[10] ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium-Z mixing parameter δm^2 <(10–30) GeV^2 (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ($b'\overline{b}'$) state is excluded for the mass range 87.7–94.7 GeV. This range depends on the potential choice.

[11] ABREU 90D assumed $m_{H^-} < m_{b'} - 3$ GeV.

[12] Superseded by ABREU 91F.

[13] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.6 and 41.4 GeV if no H^+ decays exist. For charged Higgs decays the excluded regions are between (m_{H^+} + 1.5 GeV) and 45.5 GeV.

[14] AKRAWY 90J search for isolated photons in hadronic Z decay and derive $B(Z \rightarrow b'\overline{b}') \cdot B(b' \rightarrow \gamma X)/B(Z \rightarrow \text{hadrons}) < 2.2 \times 10^{-3}$. Mass limit assumes $B(b' \rightarrow \gamma X) > 10\%$.

[15] ABE 89E search at E_{cm} = 56–57 GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

[16] ABE 89G search was at E_{cm} = 55–60.8 GeV at TRISTAN.

[17] If the photonic decay mode is large ($B(b' \rightarrow b\gamma) > 25\%$), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ($b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$) is 45.2 GeV.

[18] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[19] ADACHI 89C also gives limits for any mixture of CC and bg decays.

[20] ENO 89 search at E_{cm} = 50–60.8 at TRISTAN.

[21] ENO 89 considers arbitrary mixture of the charged current, bg, and $b\gamma$ decays.

[22] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(b') < 0.26$ (95% CL) assuming charged current decay, which translates to $m_{b'}$ > 24.4 GeV.

[23] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 23.8 GeV for charge −1/3 quarks.

[24] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, ΔR, as a function of the minimum c.m. energy (see their figure 3). Production of a pair of 1/3 charge quarks is excluded up to E_{cm} = 45.4 GeV.

[25] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)B(\text{hadrons})$ <2.4 keV CL = 95% and heavy charge 1/3 quark pair production m >21 GeV, CL = 95%.

[26] ALTHOFF 84I exclude heavy quark pair production for 7 <m <19 GeV (1/3 charge) using aplanarity distributions (CL = 95%).

REFERENCES FOR Searches for (Fourth Generation) b' Quark

ABACHI 97D PRL 78 3818 S. Abachi+ (D0 Collab.)
FROGGATT 97 ZPHY C73 333 C.D. Froggatt, D.J. Smith, H.B. Nielsen (GLAS, BOHR)
ABACHI 95F PR D52 4877 +Abbott, Abolins, Acharya, Adam, Adams+ (D0 Collab.)
ADRIANI 93G PL B313 326 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ADRIANI 93M PRPL 236 1 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
MUKHOPAD... 93 PR D48 2105 Mukhopadhyaya, Roy (TATA)
ABE 92 PRL 68 447 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
Also 92G PR D45 3921 Abe, Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 92G PR D45 3921 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
ABE 90B PRL 64 147 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 90D PL B234 382 +Amako, Arai, Asano+ (VENUS Collab.)
ABREU 90D PL B242 536 +Adam, Adami, Adye, Alekseev, Allaby+ (DELPHI Collab.)
ADACHI 90 PL B234 197 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
AKESSON 90 ZPHY C46 179 +Alitti, Ansari, Ansorge, Bagnaia+ (UA2 Collab.)
AKRAWY 90B PL B236 364 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBAJAR 90B ZPHY C48 1 +Albrow, Allkofer, Andrieu, Ankoviak+ (UA1 Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
ABE 89E PR D39 3524 +Amako, Arai, Asano, Chiba, Chiba+ (VENUS Collab.)
ABE 89G PRL 63 1776 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABRAMS 89C PRL 63 2447 +Adolphsen, Averill, Ballam+ (Mark II Collab.)
ADACHI 89C PL B229 427 +Aihara, Doser, Enomoto, Fujii+ (TOPAZ Collab.)
ENO 89 PRL 63 1910 +Auchincloss, Blanis, Bodek, Budd+ (AMY Collab.)
ALBAJAR 88 ZPHY C37 505 +Albrow, Allkofer+ (UA1 Collab.)
ALTARELLI 88 NP B308 724 +Diemoz, Martinelli, Nason (CERN, ROMA, ETH)
IGARASHI 88 PRL 60 2359 +Myung, Chiba, Hanaoka+ (AMY Collab.)
SAGAWA 88 PRL 60 93 +Mori, Abe+ (AMY Collab.)
ADEVA 86 PR D34 681 +Ansari, Becker, Becker-Szendy+ (Mark-J Collab.)
ALTHOFF 84C PL 138B 441 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84I ZPHY C22 307 +Braunschweig, Kirschfink+ (TASSO Collab.)

Free Quark Searches

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–3.

References

1. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
2. L. Lyons, Phys. Reports **129**, 225 (1985).
3. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

X-SECT (cm^2)	*CHG* (*e*/3)	*MASS* (GeV)	*ENERGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<1.3E−36	±2	45–84	130–172	e^+e^-	0	ABREU	97D	DLPH
<2.E−35	+2	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<1.E−35	+4	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<3.8E−28			14.5A	^{28}Si–Pb	0	[2] HE	91	PLAS
<3.2E−28			14.5A	^{28}Si–Cu	0	[2] HE	91	PLAS
<1.E−40	±1,2	<10		$p,\nu,\overline{\nu}$	0	BERGSMA	84B	CHRM
<1.E−36	±1,2	<9	200	μ	0	AUBERT	83C	SPEC
<2.E−10	±2,4	1–3	200	p	0	[3] BUSSIERE	80	CNTR
<5.E−38	+1,2	>5	300	p	0	[4,5] STEVENSON	79	CNTR
<1.E−33	±1	<20	52	pp	0	BASILE	78	SPEC
<9.E−39	±1,2	<6	400	p	0	[4] ANTREASYAN	77	SPEC
<8.E−35	+1,2	<20	52	pp	0	[6] FABJAN	75	CNTR
<5.E−38	−1,2	4–9	200	p	0	NASH	74	CNTR
<1.E−32	+2,4	4–24	52	pp	0	ALPER	73	SPEC
<5.E−31	+1,2,4	<12	300	p	0	LEIPUNER	73	CNTR
<6.E−34	±1,2	<13	52	pp	0	BOTT	72	CNTR
<1.E−36	−4	4	70	p	0	ANTIPOV	71	CNTR
<1.E−35	±1,2	2	28	p	0	[7] ALLABY	69B	CNTR
<4.E−37	−2	<5	70	p	0	[3] ANTIPOV	69	CNTR
<3.E−37	−1,2	2–5	70	p	0	[7] ANTIPOV	69B	CNTR
<1.E−35	+1,2	<7	30	p	0	DORFAN	65	CNTR
<2.E−35	−2	< 2.5–5	30	p	0	[8] FRANZINI	65B	CNTR
<5.E−35	+1,2	<2.2	21	p	0	BINGHAM	64	HLBC
<1.E−32	+1,2	<4.0	28	p	0	BLUM	64	HBC
<1.E−35	+1,2	<2.5	31	p	0	[8] HAGOPIAN	64	HBC
<1.E−34	+1	<2	28	p	0	LEIPUNER	64	CNTR
<1.E−33	+1,2	<2.4	24	p	0	MORRISON	64	HBC

[1] ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.
[2] HE 91 limits are for charges of the form $N\pm1/3$ from 23/3 to 38/3.
[3] Hadronic or leptonic quarks.
[4] Cross section cm^2/GeV^2.
[5] 3×10^{-5} <lifetime $< 1\times10^{-3}$ s.
[6] Includes BOTT 72 results.
[7] Assumes isotropic cm production.
[8] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT ($cm^2sr^{-1}GeV^{-1}$)	*CHG* *e*/3	*MASS* (GeV)	*ENERGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<4.E−36	−2,4	1.5–6	70	p	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	pp	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	pp	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[9] GALIK	74	CNTR
<9.E−35	−1,2		200	p	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	p	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	p	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	p	0	ANTIPOV	69B	CNTR

[9] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no "confinement."
(b) is the probability of fractional charge on nuclear fragments. Energy is in GeV/nucleon.
(c) is the 90%CL upper limit on fractionally-charged particles produced per interaction.
(d) is quarks per collision.
(e) is inclusive quark-production cross-section ratio to $\sigma(e^+e^- \to \mu^+\mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.
(h) is quark yield per π^- yield.
(i) is 2-body exclusive quark-production cross-section ratio to $\sigma(e^+e^- \to \mu^+\mu^-)$.

FLUX		*CHG* (*e*/3)	*MASS* (GeV)	*ENRGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<1.6E−3	b	see note		200	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<6.2E−4	b	see note		10.6	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<0.94E−4	e	±2	2–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.7E−4	e	±2	30–40	88–94	e^+e^-	0	AKERS	95R	OPAL
<3.6E−4	e	±4	5–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.9E−4	e	±4	30–45	88–94	e^+e^-	0	AKERS	95R	OPAL
<2.E−3	e	+1	5–40	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<6.E−4	e	+2	5–30	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<1.2E−3	e	+4	15–40	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<3.6E−4	i	+4	5.0–10.2	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<3.6E−4	i	+4	16.5–26.0	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<6.9E−4	i	+4	26.0–33.3	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<9.1E−4	i	+4	33.3–38.6	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.1E−3	i	+4	38.6–44.9	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.7E−4	b	see note		see note		0	[12] CECCHINI	93	PLAS
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	[13] GHOSH	92	EMUL
<6.4E−5	g	1			$\nu,\overline{\nu}$	1	[14] BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\overline{\nu}$	0	[14] BASILE	91	CNTR
<3.9E−5	g	1			$\nu,\overline{\nu}$	1	[15] BASILE	91	CNTR
<2.8E−5	g	2			$\nu,\overline{\nu}$	0	[15] BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[16] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[16] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<5E−2	e	2	19–27	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<5E−2	e	4	<24	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<1.E−4	e	+2	<3.5	10	e^+e^-	0	BOWCOCK	89B	CLEO
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY	89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY	89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY	89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS	89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS	89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS	89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS	89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA	89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\overline{\nu}d$	0	ALLASIA	88	BEBC
<3.E−4	b	See note		14.5	^{16}O–Pb	0	[17] HOFFMANN	88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[18] HOFFMANN	88	PLAS
<8E−5	b	19,20,22,23		200*A*			GERBIER	87	PLAS
<2.E−4	a	±1,2	<300	320	$\overline{p}p$	0	LYONS	87	MLEV
<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0	SHAW	87	MDRP
<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[19] ABACHI	86C	CNTR
<1.E−4	e	±1,2,4	<4	10	e^+e^-	0	ALBRECHT	85G	ARG

<6.E−5	b	±1,2	1	540	$p\overline{p}$	0	BANNER	85	UA2
<5.E−3	e	−4	1–8	29	e^+e^-	0	AIHARA	84	TPC
<1.E−2	e	±1,2	1–13	29	e^+e^-	0	AIHARA	84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[20] BARWICK	84	CNTR
<1.E−4	e	±2	<0.4	1.4	e^+e^-	0	BONDAR	84	OLYA
<5.E−1	e	±1,2	<13	29	e^+e^-	0	GURYN	84	CNTR
<3.E−3	b	±1,2	<2	540	$p\overline{p}$	0	BANNER	83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0	LINDGREN	83	CNTR
<3.E−3	b	> | ± 0.1|		74	^{40}Ar	0	[20] PRICE	83	PLAS
<1.E−2	e	±1,2	<14	29	e^+e^-	0	MARINI	82B	CNTR
<8.E−2	e	±1,2	<12	29	e^+e^-	0	ROSS	82	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0	WEISS	81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0	BARTEL	80	JADE
<2.E−5	g	1,2			ν	0	[14,15] BASILE	80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[21] BOZZOLI	79	CNTR
<6.E−11	f	±1	<21	52	pp	0	BASILE	78	SPEC
<5.E−3	g				ν_μ	0	BASILE	78B	CNTR
<2.E−9	f	±1	<26	62	pp	0	BASILE	77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[22] FABJAN	75	CNTR
		+1,2	>4.5		γ	0	[14,15] GALIK	74	CNTR
		+1,2	>1.5	12	e^-	0	[14,15] BELLAMY	68	CNTR
		+1,2	>0.9		γ	0	[15] BATHOW	67	CNTR
		+1,2	>0.9	6	γ	0	[15] FOSS	67	CNTR

[10] HUENTRUP 96 quote 95% CL limits for production of fragments with charge differing by as much as ±1/3 (in units of e) for charge $6 \le Z \le 10$.

[11] BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.

[12] CECCHINI 93 limit at 90%CL for $23/3 \le Z \le 40/3$, for 16*A* GeV O, 14.5*A* Si, and 200*A* S incident on Cu target. Other limits are 2.3×10^{-4} for $17/3 \le Z \le 20/3$ and $1.2 \times 10^{-4} \le Z \le 23/3$.

[13] GHOSH 92 reports measurement of spallation fragment charge based on ionization in emulsion. Out of 650 measured tracks, 2 were consistent with charge 5e/3, and 4 with 7e/3.

[14] Hadronic quark.

[15] Leptonic quark.

[16] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).

[17] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of e/3.

[18] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of e/3.

[19] Flux limits and mass range depend on charge.

[20] Bound to nuclei.

[21] Quark lifetimes $> 1 \times 10^{-8}$ s.

[22] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX (cm^{-2}sr^{-1}s^{-1})	*CHG* (*e*/3)	*MASS* (GeV)	*SHIELDING*	*EVTS*	*DOCUMENT ID*		*TECN*
<2.1E−15	±1			0	MORI	91	KAM2
<2.3E−15	±2			0	MORI	91	KAM2
<2.E−10	±1,2		0.3	0	WADA	88	CNTR
	±4		0.3	12	[23] WADA	88	CNTR
	±4		0.3	9	[24] WADA	86	CNTR
<1.E−12	±2,3/2		−70.	0	[25] KAWAGOE	84B	PLAS
<9.E−10	±1,2		0.3	0	WADA	84B	CNTR
<4.E−9	±4		0.3	7	WADA	84B	CNTR
<2.E−12	±1,2,3		−0.3 *	0	MASHIMO	83	CNTR
<3.E−10	±1,2		0.3	0	MARINI	82	CNTR
<2.E−11	±1,2			0	MASHIMO	82	CNTR
<8.E−10	±1,2		0.3	0	[25] NAPOLITANO	82	CNTR
				3	[26] YOCK	78	CNTR
<1.E−9				0	[27] BRIATORE	76	ELEC
<2.E−11	+1			0	[28] HAZEN	75	CC
<2.E−10	+1,2			0	KRISOR	75	CNTR
<1.E−7	+1,2			0	[28,29] CLARK	74B	CC
<3.E−10	+1	>20		0	KIFUNE	74	CNTR
<8.E−11	+1			0	[28] ASHTON	73	CNTR
<2.E−8	+1,2			0	HICKS	73B	CNTR
<5.E−10	+4		2.8 *	0	BEAUCHAMP	72	CNTR
<1.E−10	+1,2			0	[28] BOHM	72B	CNTR
<1.E−10	+1,2		2.8 *	0	COX	72	ELEC
<3.E−10	+2			0	CROUCH	72	CNTR
<3.E−8			7	0	[27] DARDO	72	CNTR
<4.E−9	+1			0	[28] EVANS	72	CC
<2.E−9		>10		0	[27] TONWAR	72	CNTR
<2.E−10	+1		2.8 *	0	CHIN	71	CNTR
<3.E−10	+1,2			0	[28] CLARK	71B	CC
<1.E−10	+1,2			0	[28] HAZEN	71	CC
<5.E−10	+1,2		3.5 *	0	BOSIA	70	CNTR
	+1,2	<6.5		1	[28] CHU	70	HLBC
<2.E−9	+1			0	FAISSNER	70B	CNTR
<2.E−10	+1,2		0.8 *	0	KRIDER	70	CNTR
<5.E−11	+2			4	CAIRNS	69	CC
<8.E−10	+1,2	<10		0	FUKUSHIMA	69	CNTR
	+2			1	[28,30] MCCUSKER	69	CC
<1.E−10		>5	1.7,3.6	0	[27] BJORNBOE	68	CNTR
<1.E−8	±1,2,4		6.3,.2 *	0	[25] BRIATORE	68	CNTR
<3.E−8		>2		0	FRANZINI	68	CNTR
<9.E−11	±1,2			0	GARMIRE	68	CNTR
<4.E−10	±1			0	HANAYAMA	68	CNTR
<3.E−8		>15		0	KASHA	68	OSPK
<2.E−10	+2			0	KASHA	68B	CNTR
<2.E−10	+4			0	KASHA	68C	CNTR
<2.E−10	+2		6	0	BARTON	67	CNTR
<2.E−7	+4		0.008,0.5 *	0	BUHLER	67	CNTR
<5.E−10	1,2		0.008,0.5 *	0	BUHLER	67B	CNTR
<4.E−10	+1,2			0	GOMEZ	67	CNTR
<2.E−9	+2			0	KASHA	67	CNTR
<2.E−10	+2		220	0	BARTON	66	CNTR
<2.E−9	+1,2		0.5 *	0	BUHLER	66	CNTR
<3.E−9	+1,2			0	KASHA	66	CNTR
<2.E−9	+1,2			0	LAMB	66	CNTR
<2.E−8	+1,2	>7	2.8 *	0	DELISE	65	CNTR
<5.E−8	+2	>2.5	0.5 *	0	MASSAM	65	CNTR
<2.E−8	+1		2.5 *	0	BOWEN	64	CNTR
<2.E−7	+1		0.8	0	SUNYAR	64	CNTR

[23] Distribution in celestial sphere was described as anisotropic.

[24] With telescope axis at zenith angle 40° to the south.

[25] Leptonic quarks.

[26] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.

[27] Time delayed air shower search.

[28] Prompt air shower search.

[29] Also e/4 and e/6 charges.

[30] No events in subsequent experiments.

Quark Density — Matter Searches

For a review, see SMITH 89.

QUARKS/ NUCLEON	*CHG* (*e*/3)	*MASS* (GeV)	*MATERIAL/METHOD*	*EVTS*	*DOCUMENT ID*	
<4.7E−21	±1,2		silicone oil drops	0	MAR	96
<8.E−22	+2		Si/infrared photoionization	0	PERERA	93
<5.E−27	±1,2		sea water/levitation	0	HOMER	92
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES	89
<1.E−19	±1,2		various/spectrometer	0	MILNER	87
<5.E−22	±1,2		W/levitation	0	SMITH	87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN	87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN	87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE	86
<3.E−22	±1,2		levitated niobium	0	SMITH	86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH	86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER	85
<1.E−21	±1		levitated niobium	0	SMITH	85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA	84
<5.E−22			levitated steel	0	MARINELLI	84
<9.E−20	± <13		water/oil drop	0	JOYCE	83
<2.E−21	> | ± 1/2|		levitated steel	0	LIEBOWITZ	83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG	83
<2.E−20			mercury/oil drop	0	[31] HODGES	81
1.E−20	+1		levitated niobium	4	[32] LARUE	81
1.E−20	−1		levitated niobium	4	[32] LARUE	81
<1.E−21			levitated steel	0	MARINELLI	80B
<6.E−16			helium/mass spec	0	BOYD	79
1.E−20	+1		levitated niobium	2	[32] LARUE	79
<4.E−28			earth+/ion beam	0	OGOROD...	79
<5.E−15	+1		tungs./mass spec	0	BOYD	78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD	78B
<1.E−21	±2,4		water/ion beam	0	LUND	78
<6.E−15	>1/2		levitated tungsten	0	PUTT	78
<1.E−22			metals/mass spec	0	SCHIFFER	78
<5.E−15			levitated tungsten ox	0	BLAND	77
<3.E−21			levitated iron	0	GALLINARO	77
2.E−21	−1		levitated niobium	1	[32] LARUE	77
4.E−21	+1		levitated niobium	2	[32] LARUE	77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER	77
<5.E−27			water+/ion beam	0	OGOROD...	77
<1.E−21			lunar+/ion spec	0	STEVENS	76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT	70
<5.E−19			levitated graphite	0	MORPURGO	70
<5.E−23			water+/atom beam	0	COOK	69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK	68
<1.E−17			water+/uv spec	0	RANK	68
<3.E−19	±1		levitated iron	0	STOVER	67
<1.E−10			sun/uv spec	0	[33] BENNETT	66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA	66
<1.E−16	±1		levitated graphite	0	GALLINARO	66
<1.E−22			argon/electrometer	0	HILLAS	59
	−2		levitated oil	0	MILLIKAN	10

[31] Also set limits for $Q = \pm e/6$.

[32] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.

[33] Limit inferred by JONES 77B.

REFERENCES FOR Free Quark Searches

ABREU	97D	PL B396 315	P. Abreu+	(DELPHI Collab.)
HUENTRUP	96	PR C53 358	+Weidmann, Hirzebruch, Winkel, Heinrich	(SIEG)
MAR	96	PR D53 6017	+Lee, Fleming, Case+	(SLAC, SCHAF, LANL, UCI)
AKERS	95R	ZPHY C67 203	+Alexander, Allison, Ametewee, Anderson+	(OPAL Collab.)
BUSKULIC	93C	PL B303 198	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
CECCHINI	93	ASP 1 369	S. Cecchini+	
PERERA	93	PRL 70 1053	+Betarbet, Byungsung, Coon	(PITT)
ABE	92J	PR D46 R1889	+Amidei, Anway-Weiss+	(CDF Collab.)
GHOSH	92	NC 105A 99	+Roy, Ghosh, Ghosh, Basu	(JADA, BANGB)
HOMER	92	ZPHY C55 549	+Smith, Lewin, Robertson+	(RAL, SHMP, LOQM)
BASILE	91	NC 104A 405	+Berbiers, Cara Romeo+	(BGNA, INFN, CERN, PLRM+)
HE	91	PR C44 1672	+Price	(UCB)
MATIS	91	NP A525 513c	+Pugh, Alba, Bland, Calloway+	(LBL, SFSU, UCI, LANL)
MORI	91	PR D43 2843	+Oyama, Suzuki, Takahashi+	(Kamiokande II Collab.)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
BOWCOCK	89B	PR D40 263	+Kinoshita, Mauskopf, Pipkin+	(CLEO Collab.)
CALLOWAY	89	PL B232 549	+Alba, Bland, Dickson, Hodges+	(SFSU, UCI, LBL, LANL)
JONES	89	ZPHY C43 349	+Smith, Homer, Lewin, Walford	(LOIC, RAL)
MATIS	89	PR D39 1851	+Pugh, Bland, Calloway+	(LBL, SFSU, UCI, FNAL, LANL)
NAKAMURA	89	PR D39 1261	+Kobayashi, Konaka, Imai, Masaike+	(KYOT, TMTC)
SMITH	89	ARNPS 39 73		(RAL)
ALLASIA	88	PR D37 219	+Angelini, Baldini+	(WA25 Collab.)
HOFFMANN	88	PL B200 583	+Brechtmann, Heinrich, Benton	(SIEG, USF)
PHILLIPS	88	NIM A264 125	+Fairbank, Navarro	(STAN)
WADA	88	NC 11C 229	+Yamashita, Yamamoto	(OKAY)
GERBIER	87	PRL 59 2535	G. Gerbier+	(UCB, CERN)
LYONS	87	ZPHY C36 363	+Smith, Homer, Lewin, Walford+	(OXF, RAL, LOIC)
MILNER	87	PR D36 37	+Cooper, Chang, Wilson, Labrenz, McKeown	(CIT)
SHAW	87	PR D36 3533	+Matis, Pugh, Slansky+	(UCI, LBL, LANL, SFSU)
SMITH	87	PL B197 447	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
VANPOLEN	87	PR D36 1983	+Hagstrom, Hirsch	(ANL, LBL)
ABACHI	86C	PR D33 2733	+Shor, Barasch, Carroll+	(UCLA, LBL, UCD)
SAVAGE	86	PL 167B 481	+Bland, Hodges, Huntington, Joyce+	(SFSU)
SMITH	86	PL B171 129	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
SMITH	86B	PL B181 407	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
WADA	86	NC 9C 358		(OKAY)
ALBRECHT	85G	PL 156B 134	+Binder, Harder, Hasemann+	(ARGUS Collab.)
BANNER	85	PL 156B 129	+Bloch, Borer, Borghini+	(UA2 Collab.)
MILNER	85	PRL 54 1472	+Cooper, Chang, Wilson, Labrenz, McKeown	(CIT)
SMITH	85	PL 153B 188	+Homer, Lewin, Walford, Jones	(RAL, LOIC)
AIHARA	84	PRL 52 168	+Alston-Garnjost, Badtke, Bakker+	(TPC Collab.)
AIHARA	84B	PRL 52 2332	+Alston-Garnjost, Badtke, Bakker+	(TPC Collab.)
BARWICK	84	PR D30 691	+Musser, Stevenson	(UCB)
BERGSMA	84B	ZPHY C24 217	+Allaby, Abt, Gemanov+	(CHARM Collab.)
BONDAR	84	JETPL 40 1265	+Kurdadze, Lelchuk, Panin, Sidorov+	(NOVO)
		Translated from ZETFP 40 440.		
GURYN	84	PL 139B 313	+Parker, Fries+	(FRAS, LBL, NWES, STAN, HAWA)
KAWAGOE	84B	LNC 41 604	+Mashimo, Nakamura, Nozaki, Orito	(TOKY)
KUTSCHERA	84	PR D29 791	+Schiffer, Frekers+	(ANL, FNAL)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WADA	84B	LNC 40 329	+Yamashita, Yamamoto	(OKAY)
AUBERT	83C	PL 133B 461	+Bassompierre, Becks, Best+	(EMC Collab.)
BANNER	83	PL 121B 187	+Bloch, Bonaudi, Borer+	(UA2 Collab.)
JOYCE	83	PRL 51 731	+Abrams, Bland, Johnson, Lindgren+	(SFSU)
LIEBOWITZ	83	PRL 50 1640	+Binder, Ziock	(VIRG)
LINDGREN	83	PRL 51 1621	+Joyce+	(SFSU, UCR, UCI, SLAC, LBL, LANL)
MASHIMO	83	PL 128B 327	+Orito, Kawagoe, Nakamura, Nozaki	(ICEPP)
PRICE	83	PRL 50 566	+Tincknell, Tarle, Ahlen, Frankel+	(UCB)
VANDESTEEG	83	PRL 50 1234	+Jongbloets, Wyder	(NIJM)
MARINI	82	PR D26 1777	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
MARINI	82B	PRL 48 1649	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
MASHIMO	82	JPSJ 51 3067	+Kawagoe, Koshiba	(INUS)
NAPOLITANO	82	PR D25 2837	+Besset+	(STAN, FRAS, LBL, NWES, HAWA)
ROSS	82	PL 118B 199	+Ronga, Besset+	(FRAS, LBL, NWES, STAN, HAWA)
HODGES	81	PRL 47 1651	+Abrams, Baden, Bland, Joyce+	(UCR, SFSU)
LARUE	81	PRL 46 967	+Phillips, Fairbank	(STAN)
WEISS	81	PL 101B 439	+Abrams, Alam, Blocker+	(SLAC, LBL, UCB)
BARTEL	80	ZPHY C6 295	+Canzler, Lords, Drumm+	(JADE Collab.)
BASILE	80	LNC 29 251	+Berbiers+	(BGNA, CERN, FRAS, ROMA, BARI)
BUSSIERE	80	NP B174 1	+Giacomelli, Lesquoy+	(BGNA, SACL, LAPP)
MARINELLI	80B	PL 94B 433	+Morpurgo	(GENO)
Also	80	PL 94B 427	Marinelli, Morpurgo	(GENO)
BOYD	79	PRL 43 1288	+Blatt, Donoghue, Dries, Hausman, Suiter	(OSU)
BOZZOLI	79	NP B159 363	+Bussiere, Giacomelli+	(BGNA, LAPP, SACL, CERN)
LARUE	79	PRL 42 142	+Fairbank, Phillips	(STAN)
Also	79B	PRL 42 1019	Larue, Fairbank, Phillips	
OGOROD...	79	JETP 49 953	Ogorodnikov, Samoilov, Solntsev	(KIAE)
		Translated from ZETF 76 1881.		
STEVENSON	79	PR D20 82		(LBL)
BASILE	78	NC 45A 171	+Cara-Romeo, Cifarelli, Contin+	(CERN, BGNA)
BASILE	78B	NC 45A 281	+Cara-Romeo, Cifarelli, Contin+	(CERN, BGNA)
BOYD	78	PRL 40 216	+Elmore, Melissinos, Sugarbaker	(ROCH)
BOYD	78B	PL 72B 484	+Elmore, Nitz, Olsen, Sugarbaker, Warren+	(ROCH)
LUND	78	RA 25 75	+Brandt, Fares	(MARB)
PUTT	78	PR D17 1466	+Yock	(AUCK)
SCHIFFER	78	PR D17 2241	+Renner, Gemmell, Mooring	(CHIC, ANL)
YOCK	78	PR D18 641		(AUCK)
ANTREASYAN	77	PRL 39 513	+Cocconi, Cronin, Frisch+	(EFI, PRIN)
BASILE	77	NC 40A 41	+Romeo, Cifarelli, Giusti+	(CERN, BGNA)
BLAND	77	PRL 39 369	+Bocobo, Eubank, Royer	(SFSU)
GALLINARO	77	PRL 38 1255	+Marinelli, Morpurgo	(GENO)
JONES	77B	RMP 69 717		
LARUE	77	PRL 38 1011	+Fairbank, Hebard	(STAN)
MULLER	77	Science 521	+Alvarez, Holley, Stephenson	(LBL)
OGOROD...	77	JETP 45 857	Ogorodnikov, Samoilov, Solntsev	(KIAE)
		Translated from ZETF 72 1633.		
BALDIN	76	SJNP 22 264	+Vertogradov, Vishnevsky, Grishkevich+	(JINR)
		Translated from YAF 22 512.		
BRIATORE	76	NC 31A 553	+Dardo, Piazzoli, Mannocchi+	(LCGT, FRAS, FREIB)
STEVENS	76	PR D14 716	+Schiffer, Chupka	(ANL)
ALBROW	75	NP B97 189	+Barber+	(CERN, DARE, FOM, LANC, MCHS, UTRE)
FABJAN	75	NP B101 349	+Gruhn, Peak, Sauli, Caldwell+	(CERN, MPIM)
HAZEN	75	NP B95 189	+Hodson, Winterstein, Green, Kass+	(MICH, LEED)
JOVANOV...	75	PL 56B 105	Jovanovich+	(MANI, AACH, CERN, GENO, HARV+)
KRISOR	75	NC 27A 132		(AACH3)
CLARK	74B	PR D10 2721	+Finn, Hansen, Smith	(LLL)
GALIK	74	PR D9 1856	+Jordan, Richter, Seppi, Siemann+	(SLAC, FNAL)
KIFUNE	74	JPSJ 36 629	+Hieda, Kurokawa, Tsunemoto+	(TOKY, KEK)
NASH	74	PRL 32 858	+Yamanouchi, Nease, Sculli	(FNAL, CORN, NYU)
ALPER	73	PL 46B 265	+	(CERN, LIVP, LUND, BOHR, RHEL, STOH, BERG+)
ASHTON	73	JPA 6 577	+Cooper, Parvaresh, Saleh	(DURH)
HICKS	73B	NC 14A 65	+Flint, Standil	(MANI)
LEIPUNER	73	PRL 31 1226	+Larsen, Sessoms, Smith, Williams+	(BNL, YALE)
BEAUCHAMP	72	PR D6 1211	+Bowen, Cox, Kalbach	(ARIZ)
BOHM	72B	PRL 28 326	+Diemont, Faissner, Fasold, Krisor+	(AACH)
BOTT	72	PL 40B 693	+Caldwell, Fabjan, Gruhn, Peak+	(CERN, MPIM)
COX	72	PR D6 1203	+Beauchamp, Bowen, Kalbach	(ARIZ)
CROUCH	72	PR D5 2667	+Mori, Smith	(CASE)
DARDO	72	NC 9A 319	+Navarra, Penengo, Sitte	(TORI)
EVANS	72	PRSE A70 143	+Fancey, Muir, Watson	(EDIN, LEED)
TONWAR	72	JPA 5 569	+Naranan, Sreekantan	(TATA)
ANTIPOV	71	NP B27 374	+Kachanov, Kutjin, Landsberg, Lebedev+	(SERP)
CHIN	71	NC 2A 419	+Hanayama, Hara, Higashi, Tsuji	(OSAK)
CLARK	71B	PRL 27 51	+Ernst, Finn, Griffin, Hansen, Smith+	(LLL, LBL)
HAZEN	71	PRL 26 582		(MICH)
BOSIA	70	NC 66A 167	+Briatore	(TORI)
CHU	70	PRL 24 917	+Kim, Beam, Kwak	(OSU, ROSE, KANS)
Also	70B	PRL 25 550	Allison, Derrick, Hunt, Simpson, Voyvodic	(ANL)
ELBERT	70	NP B20 217	+Erwin, Herb, Nielsen, Petrilak, Weinberg	(WISC)
FAISSNER	70B	PRL 24 1357	+Holder, Krisor, Mason, Sawaf, Umbach	(AACH3)
KRIDER	70	PR D1 835	+Bowen, Kalbach	(ARIZ)
MORPURGO	70	NIM 79 95	+Gallinaro, Palmieri	(GENO)
ALLABY	69B	NC 64A 75	+Bianchini, Diddens, Dobinson, Hartung+	(CERN)
ANTIPOV	69	PL 29B 245	+Karpov, Khromov, Landsberg, Lapshin+	(SERP)
ANTIPOV	69B	PL 30B 576	+Bolotov, Devishev, Devisheva, Isakov+	(SERP)
CAIRNS	69	PR 186 1394	+McCkusker, Peak, Woolcott	(SYDN)
COOK	69	PR 188 2092	+Depasquali, Frauenfelder, Peacock+	(ILL)
FUKUSHIMA	69	PR 178 2058	+Kifune, Kondo, Koshiba+	(TOKY)
MCCUSKER	69	PRL 23 658	+Cairns	(SYDN)
BELLAMY	68	PR 166 1391	+Hofstadter, Lakin, Perl, Toner	(STAN, SLAC)
BJORNBOE	68	NC B53 241	+Damgard, Hansen+	(BOHR, TATA, BERN, BERG)
BRAGINSK	68	JETP 27 51	+Zeldovich, Martynov, Migulin	(MOSU)
		Translated from ZETF 54 91.		
BRIATORE	68	NC 57A 850	+Castagnoli, Bollini, Massam+	(TORI, CERN, BGNA)
FRANZINI	68	PRL 21 1013	+Shulman	(COLU)
GARMIRE	68	PR 166 166	+Leong, Sreekantan	(MIT)
HANAYAMA	68	CJP 46 S734	+Hara, Higashi, Kitamura, Miono+	(OSAK)
KASHA	68	PR 172 1297	+Stefanski	(BNL, YALE)
KASHA	68B	PRL 20 217	+Larsen, Leipuner, Adair	(BNL, YALE)
KASHA	68C	CJP 46 S730	+Larsen, Leipuner, Adair	(BNL, YALE)
RANK	68	PR 176 1635		(MICH)
BARTON	67	PRSL 90 87		(NPOL)
BATHOW	67	PL 25B 163	+Freytag, Schulz, Tesch	(DESY)
BUHLER	67	NC 49A 209	+Fortunato, Massam, Zichichi	(CERN, BGNA)
BUHLER	67B	NC 51A 837	+Dalpiaz, Massam, Zichichi	(CERN, BGNA, STRB)
FOSS	67	PL 25B 166	+Garelick, Homma, Lobar, Osborne, Uglum	(MIT)
GOMEZ	67	PRL 18 1022	+Kobrak, Moline, Mullins, Orth, VanPutten+	(CIT)
KASHA	67	PR 154 1263	+Leipuner, Wangler, Alspector, Adair	(BNL, YALE)
STOVER	67	PR 164 1599	+Moran, Trischka	(SYRA)
BARTON	66	PL 21 360	+Stockel	(NPOL)
BENNETT	66	PRL 17 1196		(YALE)
BUHLER	66	NC 45A 520	+Fortunato, Massam, Muller+	(CERN, BGNA, STRB)
CHUPKA	66	PRL 17 60	+Schiffer, Stevens	(ANL)
GALLINARO	66	PL 23 609	+Morpurgo	(GENO)
KASHA	66	PR 150 1140	+Leipuner, Adair	(BNL, YALE)
LAMB	66	PRL 17 1068	+Lundy, Novey, Yovanovitch	(ANL)
DELISE	65	PR 140B 458	+Bowen	(ARIZ)
DORFAN	65	PRL 14 999	+Eades, Lederman, Lee, Ting	(COLU)
FRANZINI	65B	PRL 14 196	+Leontic, Rahm, Samios, Schwartz	(BNL, COLU)
MASSAM	65	NC 40A 589	+Muller, Zichichi	(CERN)
BINGHAM	64	PL 9 201	+Dickinson, Diebold, Koch, Leith+	(CERN, EPOL)
BLUM	64	PRL 13 353A	+Brandt, Cocconi, Czyzewski, Danysz+	(CERN)
BOWEN	64	PRL 13 728	+Delise, Kalbach, Mortara	(ARIZ)
HAGOPIAN	64	PRL 13 280	+Selove, Ehrlich, Leboy, Lanza+	(PENN, BNL)
LEIPUNER	64	PRL 12 423	+Chu, Larsen, Adair	(BNL, YALE)
MORRISON	64	PL 9 199		(CERN)
SUNYAR	64	PR 136B 1157	+Schwarzschild, Connors	(BNL)
HILLAS	59	Nature 184 B92	+Cranshaw	(AERE)
MILLIKAN	10	Phil Mag 19 209		(CHIC)

OTHER RELATED PAPERS

LYONS Review	85	PRPL C129 225		(OXF)
MARINELLI Review	82	PRPL 85 161	+Morpurgo	(GENO)

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

STRANGE MESONS ($S = \pm 1, C = B = 0$)

(continued on the next page)

• Indicates the particle is in the Meson Summary Table

CHARMED MESONS ($C = \pm1$)

CHARMED, STRANGE MESONS ($C = S = \pm1$)

BOTTOM MESONS ($B = \pm1$)

BOTTOM, STRANGE MESONS ($B = \pm1$, $S = \mp1$)

BOTTOM, CHARMED MESONS ($B = C = \pm1$)

$c\bar{c}$ MESONS

$b\bar{b}$ MESONS

• Indicates the particle is in the Meson Summary Table

NON-$q\bar{q}$ CANDIDATES

Notes in the Meson Listings

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

PSEUDOSCALAR-MESON DECAY CONSTANTS

Revised March 1998 by M. Suzuki (LBNL).

Charged mesons

The decay constant f_P for a charged pseudoscalar meson P is defined by

$$\langle 0|A_\mu(0)|P(\mathbf{q})\rangle = i f_P\, q_\mu \ , \qquad (1)$$

where A_μ is the axial-vector part of the charged weak current after a Cabibbo-Kobayashi-Maskawa mixing-matrix element $V_{qq'}$ has been removed. The state vector is normalized by $\langle P(\mathbf{q})|P(\mathbf{q}')\rangle = (2\pi)^3\, 2E_q\, \delta(\mathbf{q}-\mathbf{q}')$, and its phase is chosen to make f_P real and positive. Note, however, that in many theoretical papers our $f_P/\sqrt{2}$ is denoted by f_P.

In determining f_P experimentally, radiative corrections must be taken into account. Since the photon-loop correction introduces an infrared divergence that is canceled by soft-photon emission, we can determine f_P only from the combined rate for $P^\pm \to \ell^\pm \nu_\ell$ and $P^\pm \to \ell^\pm \nu_\ell \gamma$. This rate is given by

$$\Gamma\,(P \to \ell\nu_\ell + \ell\nu_\ell\gamma) =$$
$$\frac{G_F^2 |V_{qq'}{}^2|}{8\pi} f_P^2\, m_\ell^2\, m_P \left(1-\frac{m_\ell^2}{m_P^2}\right)^2 [1+\mathcal{O}(\alpha)] \ . \qquad (2)$$

Here m_ℓ and m_P are the masses of the lepton and meson. Radiative corrections include inner bremsstrahlung, which is independent of the structure of the meson [1-3], and also a structure-dependent term [4,5]. After radiative corrections are made, there are ambiguities in extracting f_P from experimental measurements. In fact, the definition of f_P is no longer unique.

It is desirable to define f_P such that it depends only on the properties of the pseudoscalar meson, not on the final decay products. The short-distance corrections to the fundamental electroweak constants like $G_F|V_{qq'}|$ should be separated out. Following Marciano and Sirlin [6], we define f_P with the following form for the $\mathcal{O}(\alpha)$ corrections:

$$1+\mathcal{O}(\alpha) = \left[1+\frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\rho}\right)\right]\left[1+\frac{\alpha}{\pi}F(x)\right]$$
$$\times\left\{1-\frac{\alpha}{\pi}\left[\frac{3}{2}\ln\left(\frac{m_\rho}{m_P}\right)+C_1+C_2\frac{m_\ell^2}{m_\rho^2}\ln\left(\frac{m_\rho^2}{m_\ell^2}\right)+C_3\frac{m_\ell^2}{m_\rho^2}+\ldots\right]\right\} , \qquad (3)$$

where m_ρ and m_Z are the masses of the ρ meson and Z boson. Here

$$F(x) = 3\ln x + \frac{13-19x^2}{8(1-x^2)} - \frac{8-5x^2}{2(1-x^2)^2}\, x^2 \ln x$$
$$-2\left(\frac{1+x^2}{1-x^2}\ln x + 1\right)\ln(1-x^2) + 2\left(\frac{1+x^2}{1-x^2}\right)L(1-x^2) \ ,$$

with

$$x \equiv m_\ell/m_P \ , \qquad L(z) \equiv \int_0^z \frac{\ln(1-t)}{t}\, dt \ . \qquad (4)$$

The first bracket in the expression for $1+\mathcal{O}(\alpha)$ is the short-distance electroweak correction. A quarter of $(2\alpha/\pi)\ \ln(m_Z/m_\rho)$ is subject to the QCD correction $(1-\alpha_s/\pi)$, which leads to a reduction of the total short-distance correction of 0.00033 from the electroweak contribution alone [6]. The second bracket together with the term $-(3\alpha/2\pi)\ln(m_\rho/m_P)$ in the third bracket corresponds to the radiative corrections to the point-like pion decay ($\Lambda_{\rm cutoff} \approx m_\rho$) [2]. The rest of the corrections in the third bracket are expanded in powers of m_ℓ/m_ρ. The expansion coefficients C_1, C_2, and C_3 depend on the hadronic structure of the pseudoscalar meson and in most cases cannot be computed accurately. In particular, C_1 absorbs the uncertainty in the matching energy scale between short- and long-distance strong interactions and thus is the main source of uncertainty in determining f_{π^+} accurately.

With the experimental value for the decay $\pi^+ \to \mu^+\nu_\mu + \mu^+\nu_\mu\gamma$, one obtains

$$f_{\pi^+} = 130.7 \pm 0.1 \pm 0.36 \text{ MeV} \ , \qquad (5)$$

where the first error comes from the experimental uncertainty on $|V_{ud}|$ and the second comes from the uncertainty on C_1 ($= 0 \pm 0.24$) [6]. Similarly, one obtains from the decay $K^+ \to \mu^+\nu_\mu + \mu^+\nu_\mu\gamma$ the decay constant

$$f_{K^+} = 159.8 \pm 1.4 \pm 0.44 \text{ MeV} \ , \qquad (6)$$

where the first error is due to the uncertainty on $|V_{us}|$.

For the heavy pseudoscalar mesons, uncertainties in the experimental values for the decay rates are much larger than the radiative corrections. For the D^+, only an upper bound can be obtained from the published data:

$$f_{D^+} < 310 \text{ MeV (CL} = 90\%) \ . \qquad (7)$$

For the D_s^+, the decay constant has been extracted from both the $D_s^+ \to \mu^+\nu_\mu$ and the $D_s^+ \to \tau^+\nu_\tau$ branching fractions. Two values have been reported since the last edition [7,8]:

$$f_{D_s^+} = 194 \pm 35 \pm 20 \pm 14 \text{ MeV from } D_s^+ \to \mu^+\nu_\mu \ ,$$
$$f_{D_s^+} = 309 \pm 58 \pm 33 \pm 38 \text{ MeV from } D_s^+ \to \tau^+\nu_\tau \ .$$

There are now altogether five reported values for $f_{D_s^+}$ spread over a wide range,

$$f_{D_s^+} = 194 \text{ MeV} \ \sim 430 \text{ MeV} \qquad (8)$$

with large uncertainties attached. We must wait for better data before giving a meaningful value for $f_{D_s^+}$. (See the measurements of the $D_s^+ \to \ell^+\nu_\ell$ modes in the Particle Listings for the numbers quoted by individual experiments.)

There have been many attempts to extract f_P from spectroscopy and nonleptonic decays using theoretical models. Since it is difficult to estimate uncertainties for them, we have listed here only values of decay constants that are obtained directly from the observation of $P^\pm \to \ell^\pm\nu_\ell$.

Light neutral mesons

The decay constants for the light neutral pseudoscalar mesons π^0, η, and η' are defined by

$$\langle 0|A_\mu(0)|P^0(\mathbf{q})\rangle = i(f_P/\sqrt{2})q_\mu \ , \qquad (9)$$

where A_μ is a neutral axial-vector current of octet or singlet. However f_p for the neutral mesons cannot be extracted directly from the data.

In the limit of $m_P \to 0$, the Adler-Bell-Jackiw anomaly determines f_P through the matrix element of the two-photon decay $P^0 \to \gamma\gamma$ [9,10]. The extrapolation to the mass shell is needed to extract the physical value of f_P. In the case of f_{π^0}, the extrapolation is small and the experimental uncertainty in the π^0 lifetime dominates in the uncertainty of f_{π^0}:

$$f_{\pi^0} = 130 \pm 5 \text{ MeV} \ , \qquad (10)$$

which is consistent with isospin symmetry.

For the η and η', the extrapolation to the mass shell is larger and therefore the dominance of the anomaly on the mass shell is questionable, particularly for the η'; and η–η' mixing adds to the uncertainty. If the corrections are computed for the octet with the chiral Lagrangian [11], one obtains $f_8 \approx 1.3 f_\pi$ for the decay constant of the $I = 0$ octet state. For the singlet state, *if* the $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ decay rates are fitted with the same form as the anomaly indicates, $f_1 \approx f_\pi$ would give a viable fit for $f_8 \approx 1.3 f_\pi$ and the η–η' mixing angle of $\theta_P \approx -20°$. However, because of the arbitrariness even in defining the decay constants, we do not quote numbers for f_η or $f_{\eta'}$ here.

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$\boxed{\pi^{\pm}}$

$I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

$\pi^{\pm}$ MASS

The most accurate charged pion mass measurements are based upon x-ray wavelength measurements for transitions in π^--mesonic atoms. The observed line is the blend of three components, corresponding to different K-shell occupancies. JECKELMANN 94 revisits the occupancy question, with the conclusion that two sets of occupancy ratios, resulting in two different pion masses (Solutions A and B), are equally probable. We choose the higher Solution B since only this solution is consistent with a positive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91, ASSAMAGAN 94, and ASSAMAGAN 96) for the decay of pions at rest. Earlier mass determinations with pi-mesonic atoms may have used incorrect K-shell screening corrections.

Measurements with an error of > 0.005 MeV have been omitted from this Listing.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
139.56995±0.00035 OUR FIT				
139.56995±0.00035	[1] JECKELMANN 94	CNTR	–	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •				
139.57022±0.00014	[2] ASSAMAGAN 96	SPEC	+	$\pi^+ \to \mu^+\nu_\mu$
139.56782±0.00037	[3] JECKELMANN 94	CNTR	–	π^- atom, Soln. A
139.56996±0.00067	[4] DAUM 91	SPEC	+	$\pi^+ \to \mu^+\nu$
139.56752±0.00037	[5] JECKELMANN 86B	CNTR	–	Mesonic atoms
139.5704 ±0.0011	[4] ABELA 84	SPEC	+	See DAUM 91
139.5664 ±0.0009	[6] LU 80	CNTR	–	Mesonic atoms
139.5686 ±0.0020	CARTER 76	CNTR	–	Mesonic atoms
139.5660 ±0.0024	[6,7] MARUSHEN... 76	CNTR	–	Mesonic atoms

[1] JECKELMANN 94 Solution B (dominant 2-electron K-shell occupancy), chosen for consistency with positive $m^2_{\nu_\mu}$.

[2] ASSAMAGAN 96 measures the μ^+ momentum p_μ in $\pi^+ \to \mu^+\nu_\mu$ decay at rest to be 29.79200 ± 0.00011 MeV/c. Combined with the μ^+ mass and the assumption $m_{\nu_\mu} = 0$, this gives the π^+ mass above; if $m_{\nu_\mu} > 0$, m_{π^+} given above is a lower limit. Combined instead with m_μ and (assuming *CPT*) the π^- mass of JECKELMANN 94, p_μ gives an upper limit on m_{ν_μ} (see the ν_μ).

[3] JECKELMANN 94 Solution A (small 2-electron K-shell occupancy) in combination with either the DAUM 91 or ASSAMAGAN 94 pion decay muon momentum measurement yields a significantly negative $m^2_{\nu_\mu}$. It is accordingly not used in our fits.

[4] The DAUM 91 value includes the ABELA 84 result. The value is based on a measurement of the μ^+ momentum for π^+ decay at rest, $p_\mu = 29.79179 \pm 0.00053$ MeV, uses $m_\mu = 105.658389 \pm 0.000034$ MeV, and assumes that $m_{\nu_\mu} = 0$. The last assumption means that in fact the value is a lower limit.

[5] JECKELMANN 86B gives $m_\pi/m_e = 273.12677(71)$. We use $m_e = 0.51099906(15)$ MeV from COHEN 87. The authors note that two solutions for the probability distribution of K-shell occupancy fit equally well, and use other data to choose the lower of the two possible $\pi^{\pm}$ masses.

[6] These values are scaled with a new wavelength-energy conversion factor $V\lambda = 1.23984244(37) \times 10^{-6}$ eV m from COHEN 87. The LU 80 screening correction relies upon a theoretical calculation of inner-shell refilling rates.

[7] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration γ energies. Error increased from 0.0017 MeV to include QED calculation error of 0.0017 MeV (12 ppm).

$m_{\pi^+} - m_{\mu^+}$

Measurements with an error > 0.05 MeV have been omitted from this Listing.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
33.91157±0.00067		[8] DAUM 91	SPEC	+	$\pi^+ \to \mu^+\nu$
33.9111 ±0.0011		ABELA 84	SPEC		See DAUM 91
33.925 ±0.025		BOOTH 70	CNTR	+	Magnetic spect.
33.881 ±0.035	145	HYMAN 67	HEBC	+	K^- He

[8] The DAUM 91 value assumes that $m_{\nu_\mu} = 0$ and uses our $m_\mu = 105.658389 \pm 0.000034$ MeV.

$(m_{\pi^+} - m_{\pi^-})\ /\ m_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*
2±5	AYRES 71	CNTR

$\pi^{\pm}$ MEAN LIFE

Measurements with an error > 0.02×10^{-8} s have been omitted.

VALUE (10^{-8} s)	DOCUMENT ID		TECN	CHG	COMMENT
2.6033 ±0.0005 OUR AVERAGE	Error includes scale factor of 1.2.				
2.60361±0.00052	[9] KOPTEV	95	SPEC	+	Surface μ^+'s
2.60231±0.00050±0.00084	NUMAO	95	SPEC	+	Surface μ^+'s
2.609 ±0.008	DUNAITSEV	73	CNTR	+	
2.602 ±0.004	AYRES	71	CNTR	±	
2.604 ±0.005	NORDBERG	67	CNTR	+	
2.602 ±0.004	ECKHAUSE	65	CNTR	+	

• • • We do not use the following data for averages, fits, limits, etc. • • •

2.640 ±0.008	[10] KINSEY	66	CNTR	+	

[9] KOPTEV 95 combines the statistical and systematic errors; the statistical error dominates.

[10] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-4})	DOCUMENT ID		TECN
5.5± 7.1	AYRES	71	CNTR

• • • We do not use the following data for averages, fits, limits, etc. • • •

−14 ±29	PETRUKHIN	68	CNTR
40 ±70	BARDON	66	CNTR
23 ±40	[11] LOBKOWICZ	66	CNTR

[11] This is the most conservative value given by LOBKOWICZ 66.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$		[a]	(99.98770±0.00004) %	
Γ_2	$\mu^+\nu_\mu\gamma$		[b]	(1.24 ±0.25) × 10^{-4}	
Γ_3	$e^+\nu_e$		[a]	(1.230 ±0.004) × 10^{-4}	
Γ_4	$e^+\nu_e\gamma$		[b]	(1.61 ±0.23) × 10^{-7}	
Γ_5	$e^+\nu_e\pi^0$			(1.025 ±0.034) × 10^{-8}	
Γ_6	$e^+\nu_e e^+ e^-$			(3.2 ±0.5) × 10^{-9}	
Γ_7	$e^+\nu_e\nu\overline{\nu}$			< 5 × 10^{-6}	90%
	Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
Γ_8	$\mu^+\overline{\nu}_e$	*L*	[c]	< 1.5 × 10^{-3}	90%
Γ_9	$\mu^+\nu_e$	*LF*	[c]	< 8.0 × 10^{-3}	90%
Γ_{10}	$\mu^- e^+ e^+ \nu$	*LF*		< 1.6 × 10^{-6}	90%

[a] Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

[b] See the Particle Listings below for the energy limits used in this measurement; low-energy γ's are not included.

[c] Derived from an analysis of neutrino-oscillation experiments.

π^+ BRANCHING RATIOS

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_3/Γ

See note [a] in the list of π^+ decay modes just above, and see also the next block of data.

VALUE (units 10^{-4})	DOCUMENT ID
1.230±0.004 OUR EVALUATION	

$[\Gamma(e^+\nu_e) + \Gamma(e^+\nu_e\gamma)]/[\Gamma(\mu^+\nu_\mu) + \Gamma(\mu^+\nu_\mu\gamma)]$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

See note [a] in the list of π^+ decay modes above. See NUMAO 92 for a discussion of e-μ universality.

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.230 ±0.004 OUR AVERAGE					
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO	Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR	Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR	Stopping π^+

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.273 ±0.028	11k	[12] DICAPUA	64	CNTR	
1.21 ±0.07		ANDERSON	60	SPEC	

[12] DICAPUA 64 has been updated using the current mean life.

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.24±0.25	26	CASTAGNOLI	58	EMUL	$KE_\mu < 3.38$ MeV

$\Gamma(e^+\nu_e\gamma)/\Gamma_{\text{total}}$ — Γ_4/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
16.1±2.3		[13] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^-\overline{\nu}_e\gamma$

• • • We do not use the following data for averages, fits, limits, etc. • • •

5.6±0.7	226	[14] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

[13] BOLOTOV 90B is for $E_\gamma > 21$ MeV, $E_e > 70 - 0.8\,E_\gamma$.

[14] STETZ 78 is for an $e^-\gamma$ opening angle > 132°. Obtains 3.7 when using same cutoffs as DEPOMMIER 63B.

$\Gamma(e^+\nu_e\pi^0)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.025±0.034 OUR AVERAGE						
1.026±0.039	1224	[15] MCFARLANE	85	CNTR	+	Decay in flight
$1.00\ {}^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[16] BACASTOW	65	OSPK	+	
1.10 ±0.26		[16] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[16] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[16] BARTLETT	64	OSPK	+	

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.15 ±0.22	52	[16] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

[15] MCFARLANE 85 combines a measured rate (0.394 ± 0.015)/s with 1982 PDG mean life.

[16] DEPOMMIER 68 says the result of DEPOMMIER 63 is at least 10% too large because of a systematic error in the π^0 detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

$\Gamma(e^+\nu_e e^+ e^-)/\Gamma(\mu^+\nu_\mu)$ — Γ_6/Γ_1

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.2 ±0.5 ±0.2		98	EGLI	89	SPEC	Uses $R_{PCAC} = 0.068 \pm 0.004$

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.46±0.16±0.07		7	[17] BARANOV	92	SPEC	Stopped π^+
< 4.8	90		KORENCHE...	76B	SPEC	
<34	90		KORENCHE...	71	OSPK	

[17] This measurement by BARANOV 92 is of the structure-dependent part of the decay. The value depends on values assumed for ratios of form factors.

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<5	90	PICCIOTTO	88	SPEC

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[18] COOPER	82	HLBC	Wideband ν beam

[18] COOPER 82 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton number violation.

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ — Γ_9/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8.0	90	[19] COOPER	82	HLBC	Wideband ν beam

[19] COOPER 82 limit on ν_e observation is here interpreted as a limit on lepton family number violation.

$\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
<1.6	90	BARANOV	91B	SPEC	+

• • • We do not use the following data for averages, fits, limits, etc. • • •

<7.7	90	KORENCHE...	87	SPEC	+

π^+ — POLARIZATION OF EMITTED μ^+

$\pi^+ \rightarrow \mu^+\nu$

Tests the Lorentz structure of leptonic charged weak interactions.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

<(−0.9959)	90	[20] FETSCHER	84	RVUE	+	
−0.99±0.16		[21] ABELA	83	SPEC	−	μ *X*-rays

[20] FETSCHER 84 uses only the measurement of CARR 83.

[21] Sign of measurement reversed in ABELA 83 to compare with μ^+ measurements.

$\pi^\pm \to \ell^\pm \nu\gamma$ AND $K^\pm \to \ell^\pm \nu\gamma$ FORM FACTORS

Written by H.S. Pruys (Zürich University).

In the radiative decays $\pi^\pm \to \ell^\pm \nu\gamma$ and $K^\pm \to \ell^\pm \nu\gamma$, where ℓ is an e or a μ and γ is a real or virtual photon (e^+e^- pair), both the vector and the axial-vector weak hadronic currents contribute to the decay amplitude. Each current gives a structure-dependent term (SD_V and SD_A) from virtual hadronic states, and the axial-vector current also gives a contribution from inner bremsstrahlung (IB) from the lepton and meson. The IB amplitudes are determined by the meson decay constants f_π and f_K [1]. The SD_V and SD_A amplitudes are parameterized in terms of the vector form factor F_V and the axial-vector form factors F_A and R [1-4]:

$$M(\mathrm{SD}_V) = \frac{-eG_F V_{qq'}}{\sqrt{2}\, m_P} \epsilon^\mu \ell^\nu F_V \epsilon_{\mu\nu\sigma\tau} k^\sigma q^\tau ,$$

$$M(\mathrm{SD}_A) = \frac{-ie G_F V_{qq'}}{\sqrt{2}\, m_P} \epsilon^\mu \ell^\nu \{F_A [(s-t) g_{\mu\nu} - q_\mu k_\nu] + R\, t\, g_{\mu\nu}\} .$$

Here $V_{qq'}$ is the Cabibbo-Kobayashi-Maskawa mixing-matrix element; ϵ^μ is the polarization vector of the photon (or the effective vertex, $\epsilon^\mu = (e/t)\overline{u}(p_-)\gamma^\mu v(p_+)$, of the e^+e^- pair); $\ell^\nu = \overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_\ell)$ is the lepton-neutrino current; q and k are the meson and photon four-momenta, with $s = q\cdot k$ and $t = k^2 (= (p_+ + p_-)^2)$; and P stands for π or K. In the analysis of data, the s and t dependence of the form factors is neglected, which is a good approximation for pions [2] but not for kaons [4]. The pion vector form factor F_V^π is related via CVC to the π^0 lifetime, $|F_V^\pi| = (1/\alpha)\sqrt{2\Gamma_{\pi^0}/\pi m_{\pi^0}}$ [1]. PCAC relates R to the electromagnetic radius of the meson [2,4], $R^P = \frac{1}{3} m_P f_P \langle r_P^2 \rangle$. The calculation of the other form factors, F_A^π, F_V^K, and F_A^K, is model dependent [1,4].

When the photon is real, the partial decay rate can be given analytically [1,5]:

$$\frac{d^2\Gamma_{P\to\ell\nu\gamma}}{dx dy} = \frac{d^2\left(\Gamma_{\mathrm{IB}} + \Gamma_{\mathrm{SD}} + \Gamma_{\mathrm{INT}}\right)}{dx dy} ,$$

where $\Gamma_{\mathrm{IB}}, \Gamma_{\mathrm{SD}}$, and Γ_{INT} are the contributions from inner bremsstrahlung, structure-dependent radiation, and their interference, and the Γ_{SD} term is given by

$$\frac{d^2\Gamma_{\mathrm{SD}}}{dx dy} = \frac{\alpha}{8\pi}\Gamma_{P\to\ell\nu} \frac{1}{r(1-r)^2} \left(\frac{m_P}{f_P}\right)^2 \times \left[(F_V + F_A)^2\, \mathrm{SD}^+ + (F_V - F_A)^2\, \mathrm{SD}^-\right] .$$

Here

$$\mathrm{SD}^+ = (x + y - 1 - r)\left[(x+y-1)(1-x) - r\right] ,$$

$$\mathrm{SD}^- = (1 - y + r)\left[(1-x)(1-y) + r\right] ,$$

where $x = 2E_\gamma/m_P$, $y = 2E_\ell/m_P$, and $r = (m_\ell/m_P)^2$.

In $\pi^\pm \to e^\pm \nu\gamma$ and $K^\pm \to e^\pm \nu\gamma$ decays, the interference terms are small, and thus only the absolute values $|F_A + F_V|$ and $|F_A - F_V|$ can be obtained. In $K^\pm \to \mu^\pm \nu\gamma$ decay, the interference term is important, and thus the signs of F_V and F_A can be obtained. In $\pi^\pm \to \mu^\pm \nu\gamma$ decay, bremsstrahlung completely dominates. In $\pi^\pm \to e^\pm \nu e^+e^-$ and $K^\pm \to \ell^\pm \nu e^+e^-$ decays, all three form factors, F_V, F_A, and R, can be determined.

We give the $\pi^\pm$ form factors F_V, F_A, and R in the Listings below. In the $K^\pm$ Listings, we give the sum $F_A + F_V$ and difference $F_A - F_V$.

The electroweak decays of the pseudoscalar mesons are investigated to learn something about the unknown hadronic structure of these mesons, assuming a standard $V-A$ structure of the weak leptonic current. The experiments are quite difficult, and it is not meaningful to analyse the results using parameters for both the hadronic structure (decay constants, form factors) and the leptonic weak current (*e.g.*, to add pseudoscalar or tensor couplings to the $V-A$ coupling). Deviations from the $V-A$ interactions are much better studied in purely leptonic systems such as muon decay.

References

1. D.A. Bryman *et al.*, Phys. Reports **88**, 151 (1982). See also our note on "Pseudoscalar-Meson Decay Constants," above.
2. A. Kersch and F. Scheck, Nucl. Phys. **B263**, 475 (1986).
3. W.T. Chu *et al.*, Phys. Rev. **166**, 1577 (1968).
4. D.Yu. Bardin and E.A. Ivanov, Sov. J. Part. Nucl. **7**, 286 (1976).
5. S.G. Brown and S.A. Bludman, Phys. Rev. **136**, B1160 (1964).

$\pi^\pm$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.017±0.008 OUR AVERAGE				
0.014±0.009		[22] BOLOTOV 90B	SPEC	17 GeV $\pi^- \to e^-\overline{\nu}_e\gamma$
$0.023^{+0.015}_{-0.013}$	98	EGLI 89	SPEC	$\pi^+ \to e^+\nu_e e^+e^-$

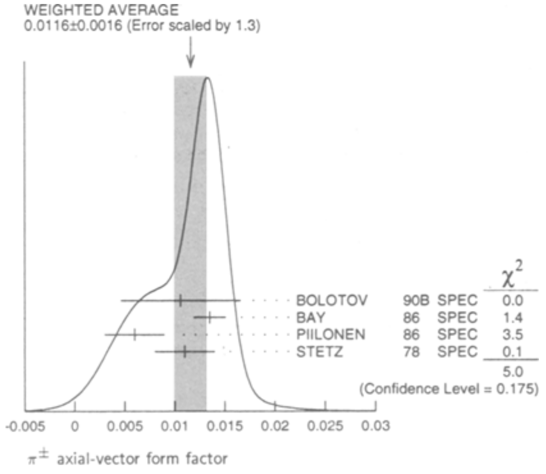
[22] BOLOTOV 90B only determines the absolute value.

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0116±0.0016 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
0.0106±0.0060		[23] BOLOTOV 90B	SPEC	17 GeV $\pi^- \to e^-\overline{\nu}_e\gamma$
0.0135±0.0016		[23] BAY 86	SPEC	$\pi^+ \to e^+\nu\gamma$
0.006 ±0.003		[23] PIILONEN 86	SPEC	$\pi^+ \to e^+\nu\gamma$
0.011 ±0.003		[23,24] STETZ 78	SPEC	$\pi^+ \to e^+\nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.021\ {}^{+0.011}_{-0.013}$	98	EGLI 89	SPEC	$\pi^+ \to e^+\nu_e e^+e^-$

[23] Using the vector form factor from CVC prediction $F_V = 0.0259 \pm 0.0005$. Only the absolute value of F_A is determined.

[24] The result of STETZ 78 has a two-fold ambiguity. We take the solution compatible with later determinations.



R, SECOND AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.059^{+0.009}_{-0.008}$	98	EGLI	89	SPEC	$\pi^+ \to e^+ \nu_e e^+ e^-$

$\pi^{\pm}$ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

ASSAMAGAN	96	PR D53 6065	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
KOPTEV	95	JETPL 61 877	+Mikirtych'yants, Shcherbakov+	(PNPI)
		Translated from ZETFP 61 865.		
NUMAO	95	PR D52 4855	+Macdonald, Marshall, Olin, Fujiwara	(TRIU, BRCO)
ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
CZAPEK	93	PRL 70 17	+Federspiel, Flueckiger, Frei+	(BERN, VILL)
BARANOV	92	SJNP 55 1644	+Vanko, Glazov, Evtukhovich+	(JINR)
		Translated from YAF 55 2940.		
BRITTON	92	PRL 68 3000	+Ahmad, Bryman, Burnham+	(TRIU, CARL)
Also	94	PR D49 28	Britton, Ahmad, Bryman+	(TRIU, CARL)
NUMAO	92	MPL A7 3357		(TRIU)
BARANOV	91B	SJNP 54 790	+Kisel, Korenchenko, Kuchinskii+	(JINR)
		Translated from YAF 54 1298.		
DAUM	91	PL B265 425	+Frosch, Herter, Janousch, Kettle	(VILL)
BOLOTOV	90B	PL B243 308	+Gninenko, Djilkibaev, Isakov+	(INRM)
EGLI	89	PL B222 533	+Engfer, Grab, Hermes, Kraus+	(SINDRUM Collab.)
Also	86	PL B175 97	Egli, Engfer, Grab, Hermes+	(AACH3, ETH, SIN, ZURI)
PDG	88	PL B204	Yost, Barnett+	(LBL+)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
KORENCHE...	87	SJNP 46 192	Korenchenko, Kostin, Mzhaviya+	(JINR)
		Translated from YAF 46 313.		
BAY	86	PL B174 445	+Ruegger, Gabioud, Joseph, Loude+	(LAUS, ZURI)
BRYMAN	86	PR D33 1211	+Dubois, Macdonald, Numao+	(TRIU, CNRC)
Also	83	PRL 50 7	Bryman, Dubois, Numao, Olaniya+	(TRIU, CNRC)
JECKELMANN	86B	NP A457 709	+Beer, Chambrier, Elsenhans+	(ETH, FRIB)
Also	86	PRL 56 1444	Jeckelmann, Nakada, Beer+	(ETH, FRIB)
PIILONEN	86	PRL 57 1402	+Bolton, Cooper, Frank+	(LANL, TEMP, CHIC)
MCFARLANE	85	PR D32 547	+Auerbach, Gaille+	(TEMP, LANL)
ABELA	84	PL 146B 431	+Daum, Eaton, Frosch, Jost, Kettle+	(SIN)
Also	78	PL 74B 126	Daum, Eaton, Frosch, Hirschmann+	(SIN)
Also	79	PR D20 2692	Daum, Eaton, Frosch, Hirschmann+	(SIN)
FETSCHER	84	PL 140B 117		(ETH)
ABELA	83	NP A395 413	+Backenstoss, Kunold, Simons+	(BASL, KARLK, KARLE)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
COOPER	82	PL 112B 97	+Guy, Michette, Tyndel, Venus	(RL)
LU	80	PRL 45 1066	+Delker, Dugan, Wu, Caffrey+	(YALE, COLU, JHU)
STETZ	78	NP B138 285	+Carroll, Ortendahl, Perez-Mendez+	(LBL, UCLA)
CARTER	76	PRL 37 1380	+Dixit, Sundaresan+	(CARL, CNRC, CHIC, CIT)
KORENCHE...	76B	JETP 44 35	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from ZETF 71 69.		
MARUSHEN...	76	JETPL 23 72	Marushenko, Mezentsev, Petrunin+	(PNPI)
		Translated from ZETFP 23 80.		
Also	76	Private Comm.	Shafer	(FNAL)
Also	78	Private Comm.	Smirnov	(PNPI)
DUNAITSEV	73	SJNP 16 292	+Prokoshkin, Razuvaev+	(SERP)
		Translated from YAF 16 524.		
AYRES	71	PR D3 1051	+Cormack, Greenberg, Kenney+	(LRL, UCSB)
Also	67	PR 157 1288	Ayres, Caldwell, Greenberg, Kenney, Kurz+	(LRL)
Also	68	PRL 21 261	Ayres, Cormack, Greenberg+	(LRL, UCSB)
Also	69	Thesis UCRL 18369	Ayres	(LRL)
Also	69	PRL 23 1267	Greenberg, Ayres, Cormack+	(LRL, UCSB)
KORENCHE...	71	SJNP 13 189	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from YAF 13 339.		
BOOTH	70	PL 32B 723	+Johnson, Williams, Wormald	(LIVP)
DEPOMMIER	68	NP B4 189	+Duclos, Heintze, Kleinknecht+	(CERN)
PETRUKHIN	68	JINR P1 3862	+Rykalin, Khazins, Cisek	(JINR)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
NORDBERG	67	PL 24B 594	+Lobkowicz, Burman	(ROCH)
BARDON	66	PRL 16 775	+Dore, Dorfan, Krieger+	(COLU)
KINSEY	66	PR 144 1132	+Lobkowicz, Nordberg	(ROCH)
LOBKOWICZ	66	PRL 17 548	+Melissinos, Nagashima+	(ROCH, BNL)
BACASTOW	65	PR 139B 407	+Ghesquiere, Wiegand, Larsen	(LRL, SLAC)
BERTRAM	65	PR 139B 617	+Meyer, Carrigan+	(MICH, CMU)
DUNAITSEV	65	JETP 20 58	+Petrukhin, Prokoshkin+	(JINR)
		Translated from ZETF 47 84.		
ECKHAUSE	65	PL 19 348	+Harris, Shuler+	(WILL)
BARTLETT	64	PR 136B 1452	+Devons, Meyer, Rosen	(COLU)
DICAPUA	64	PR 133B 1333	+Garland, Pondrom, Strelzoff	(COLU)
Also	86	Private Comm.	Pondrom	(WISC)
DEPOMMIER	63	PL 5 61	+Heintze, Rubbia, Soergel	(CERN)
DEPOMMIER	63B	PL 7 285	+Heintze, Rubbia, Soergel	(CERN)
ANDERSON	60	PR 119 2050	+Fujii, Miller+	(EFI)
CASTAGNOLI	58	PR 112 1779	+Muchnik	(ROMA)

π^0

$$I^G(J^{PC}) = 1^-(0^{-+})$$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

π^0 MASS

The value is calculated from $m_{\pi^{\pm}}$ and $(m_{\pi^{\pm}} - m_{\pi^0})$. See notes under the $\pi^{\pm}$ Mass Listings concerning recent revision of the charged pion mass.

VALUE (MeV)	DOCUMENT ID
134.9764±0.0006 OUR FIT	

$m_{\pi^{\pm}} - m_{\pi^0}$

Measurements with an error > 0.01 MeV have been omitted.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.5936 ±0.0005 OUR FIT				
4.5936 ±0.0005 OUR AVERAGE				
4.59364±0.00048	CRAWFORD	91	CNTR	$\pi^- p \to \pi^0 n$, n TOF
4.5930 ±0.0013	CRAWFORD	86	CNTR	$\pi^- p \to \pi^0 n$, n TOF
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.59366±0.00048	CRAWFORD	88B	CNTR	See CRAWFORD 91
4.6034 ±0.0052	VASILEVSKY	66	CNTR	
4.6056 ±0.0055	CZIRR	63	CNTR	

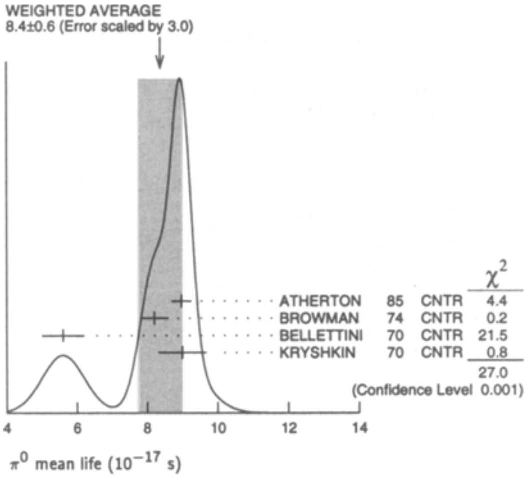
π^0 MEAN LIFE

Measurements with an error > 1×10^{-17} s have been omitted.

VALUE (10^{-17} s)	EVTS	DOCUMENT ID		TECN	COMMENT
8.4 ±0.6 OUR AVERAGE	Error includes scale factor of 3.0. See the ideogram below.				
8.97±0.22±0.17		ATHERTON	85	CNTR	
8.2 ±0.4		[1] BROWMAN	74	CNTR	Primakoff effect
5.6 ±0.6		BELLETTINI	70	CNTR	Primakoff effect
9 ±0.68		KRYSHKIN	70	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.4 ±0.5 ±0.5	1182	[2] WILLIAMS	88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$

[1] BROWMAN 74 gives a π^0 width $\Gamma = 8.02 \pm 0.42$ eV. The mean life is $\hbar/\Gamma$.

[2] WILLIAMS 88 gives $\Gamma(\gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV. We give here $\tau = \hbar/\Gamma(\text{total})$.



π^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ		(98.798 ± 0.032) %	S=1.1
Γ_2	$e^+ e^- \gamma$		(1.198 ± 0.032) %	S=1.1
Γ_3	γ positronium		$(1.82 \pm 0.29) \times 10^{-9}$	
Γ_4	$e^+ e^+ e^- e^-$		$(3.14 \pm 0.30) \times 10^{-5}$	
Γ_5	$e^+ e^-$		$(7.5 \pm 2.0) \times 10^{-8}$	
Γ_6	4γ		$< 2 \times 10^{-8}$	CL=90%
Γ_7	$\nu\overline{\nu}$		[a] $< 8.3 \times 10^{-7}$	CL=90%
Γ_8	$\nu_e \overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%
Γ_9	$\nu_\mu \overline{\nu}_\mu$		$< 3.1 \times 10^{-6}$	CL=90%
Γ_{10}	$\nu_\tau \overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
Γ_{11}	3γ	*C*	$< 3.1 \times 10^{-8}$	CL=90%
Γ_{12}	$\mu^+ e^-$			
Γ_{13}	$\mu^+ e^- + e^- \mu^+$	*LF*	$< 1.72 \times 10^{-8}$	CL=90%

[a] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the Particle Listings below.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 1.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_2 & -100 & \\ x_4 & -1 & 0 \\ \hline & x_1 & x_2 \end{array}$$

π^0 BRANCHING RATIOS

$\Gamma(e^+e^-\gamma)/\Gamma(2\gamma)$ — Γ_2/Γ_1

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.213±0.033 OUR FIT	Error includes scale factor of 1.1.			
1.213±0.030 OUR AVERAGE				
1.25 ±0.04		SCHARDT 81	SPEC	$\pi^- p \to n\pi^0$
1.166±0.047	3071	[3] SAMIOS 61	HBC	$\pi^- p \to n\pi^0$
1.17 ±0.15	27	BUDAGOV 60	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.196		JOSEPH 60	THEO	QED calculation

[3] SAMIOS 61 value uses a Panofsky ratio = 1.62.

$\Gamma(\gamma\,\text{positronium})/\Gamma(2\gamma)$ — Γ_3/Γ_1

VALUE (units 10^{-9})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.84±0.29	277	AFANASYEV 90	CNTR	pC 70 GeV

$\Gamma(e^+e^+e^-e^-)/\Gamma(2\gamma)$ — Γ_4/Γ_1

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*	*TECN*
3.18±0.30 OUR FIT			
3.18±0.30	146	[4] SAMIOS 62B	HBC

[4] SAMIOS 62B value uses a Panofsky ratio = 1.62.

$\Gamma(e^+e^-)/\Gamma_{\rm total}$ — Γ_5/Γ

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
7.5±2.0 OUR AVERAGE				
6.9±2.3±0.6	21	[5] DESHPANDE 93	SPEC	$K^+ \to \pi^+\pi^0$
$8.8^{+4.5}_{-3.2}\pm0.6$	8	[6] MCFARLAND 93	SPEC	$K^0_L \to 3\pi^0$ in flight

[5] The DESHPANDE 93 result with bremsstrahlung radiative corrections is $(8.0 \pm 2.6 \pm 0.6) \times 10^{-8}$.

[6] The MCFARLAND 93 result with radiative corrections and excluding $[m_{ee}/m_{\pi^0}]^2 < 0.95$ is $(7.6^{+3.9}_{-2.8} \pm 0.5) \times 10^{-8}$.

$\Gamma(e^+e^-)/\Gamma(2\gamma)$ — Γ_5/Γ_1

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.3	90		NIEBUHR 89	SPEC	$\pi^- p \to \pi^0 n$ at rest
<5.3	90		ZEPHAT 87	SPEC	$\pi^- p \to \pi^0 n$ 0.3 GeV/c
1.7 ±0.6 ±0.3		59	FRANK 83	SPEC	$\pi^- p \to n\pi^0$
1.8 ±0.6		58	MISCHKE 82	SPEC	See FRANK 83
$2.23^{+2.40}_{-1.10}$	90	8	FISCHER 78B	SPRK	$K^+ \to \pi^+\pi^0$

$\Gamma(4\gamma)/\Gamma_{\rm total}$ — Γ_6/Γ

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 2	90		MCDONOUGH 88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<160	90		BOLOTOV 86C	CALO	
<440	90	0	AUERBACH 80	CNTR	

$\Gamma(\nu\overline{\nu})/\Gamma_{\rm total}$ — Γ_7/Γ

The astrophysical and cosmological limits are many orders of magnitude lower, but we use the best laboratory limit for the Summary Tables.

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 0.83	90		[7] ATIYA 91	B787	$K^+ \to \pi^+\nu\nu'$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 2.9 \times 10^{-7}$			[8] LAM 91		Cosmological limit
$< 3.2 \times 10^{-7}$			[9] NATALE 91		SN 1987A
< 6.5	90		DORENBOS... 88	CHRM	Beam dump, prompt ν
<24	90	0	[7] HERCZEG 81	RVUE	$K^+ \to \pi^+\nu\nu'$

[7] This limit applies to all possible $\nu\nu'$ states as well as to other massless, weakly interacting states.

[8] LAM 91 considers the production of right-handed neutrinos produced from the cosmic thermal background at the temperature of about the pion mass through the reaction $\gamma\gamma \to \pi^0 \to \nu\overline{\nu}$.

[9] NATALE 91 considers the excess energy-loss rate from SN 1987A if the process $\gamma\gamma \to \pi^0 \to \nu\overline{\nu}$ occurs, permitted if the neutrinos have a right-handed component. As pointed out in LAM 91 (and confirmed by Natale), there is a factor 4 error in the NATALE 91 published result (0.8×10^{-7}).

$\Gamma(\nu_e\overline{\nu}_e)/\Gamma_{\rm total}$ — Γ_8/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.7	90	DORENBOS... 88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.1	90	[10] HOFFMAN 88	RVUE	Beam dump, prompt ν

[10] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\mu\overline{\nu}_\mu)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3.1	90	[11] HOFFMAN 88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7.8	90	DORENBOS... 88	CHRM	Beam dump, prompt ν

[11] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\tau\overline{\nu}_\tau)/\Gamma_{\rm total}$ — Γ_{10}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<2.1	90	[12] HOFFMAN 88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.1	90	DORENBOS... 88	CHRM	Beam dump, prompt ν

[12] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(3\gamma)/\Gamma_{\rm total}$ — Γ_{11}/Γ

Forbidden by *C* invariance.

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 3.1	90		MCDONOUGH 88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 38	90	0	HIGHLAND 80	CNTR	
<150	90	0	AUERBACH 78	CNTR	
<490	90	0	[13] DUCLOS 65	CNTR	
<490	90		[13] KUTIN 65	CNTR	

[13] These experiments give $B(3\gamma/2\gamma) < 5.0 \times 10^{-6}$.

$\Gamma(\mu^+e^-)/\Gamma_{\rm total}$ — Γ_{12}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<16	90	LEE 90	SPEC	$K^+ \to \pi^+\mu^+e^-$
<78	90	CAMPAGNARI 88	SPEC	See LEE 90

$[\Gamma(\mu^+e^-) + \Gamma(e^-\mu^+)]/\Gamma_{\rm total}$ — Γ_{13}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 17.2	90	KROLAK 94	E799	In $K^0_L \to 3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<140		HERCZEG 84	RVUE	$K^+ \to \pi^+\mu e$
$< 2 \times 10^{-6}$		HERCZEG 84	THEO	$\mu^- \to e^-$ conversion
< 70	90	BRYMAN 82	RVUE	$K^+ \to \pi^+\mu e$

π^0 ELECTROMAGNETIC FORM FACTOR

The amplitude for the process $\pi^0 \to e^+e^-\gamma$ contains a form factor $F(x)$ at the $\pi^0\gamma\gamma$ vertex, where $x = [m_{e^+e^-}/m_{\pi^0}]^2$. The parameter *a* in the linear expansion $F(x) = 1 + ax$ is listed below.

All the measurements except that of BEHREND 91 are in the time-like region of momentum transfer.

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.032 ±0.004 OUR AVERAGE				
+0.026 ±0.024 ±0.048	7548	FARZANPAY 92	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.025 ±0.014 ±0.026	54k	MEIJERDREES 92B	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.0326±0.0026±0.0026	127	[14] BEHREND 91	CELL	$e^+e^- \to e^+e^-\pi^0$
−0.11 ±0.03 ±0.08	32k	FONVIEILLE 89	SPEC	Radiation corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.12\ ^{+0.05}_{-0.04}$		[15] TUPPER 83	THEO	FISCHER 78 data
+0.10 ±0.03	31k	[16] FISCHER 78	SPEC	Radiation corr.
+0.01 ±0.11	2200	DEVONS 69	OSPK	No radiation corr.
−0.15 ±0.10	7676	KOBRAK 61	HBC	No radiation corr.
−0.24 ±0.16	3071	SAMIOS 61	HBC	No radiation corr.

[14] BEHREND 91 estimates that their systematic error is of the same order of magnitude as their statistical error, and so we have included a systematic error of this magnitude. The value of *a* is obtained by extrapolation from the region of large space-like momentum transfer assuming vector dominance.

[15] TUPPER 83 is a theoretical analysis of FISCHER 78 including 2-photon exchange in the corrections.

[16] The FISCHER 78 error is statistical only. The result without radiation corrections is $+0.05 \pm 0.03$.

π^0 REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

KROLAK 94 PL B320 407 + (EFI, UCLA, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
DESHPANDE 93 PRL 71 27 +Alliegro, Chaloupka+ (BNL E851 Collab.)
MCFARLAND 93 PRL 71 31 + (EFI, UCLA, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
FARZANPAY 92 PL B278 413 + (ORST, TRIU, BRCO, QUKI, LBL, BIRM, OXF)
MEIJERDREES 92B PR D45 1439 Meijer Drees, Waltham+ (PSI SINDRUM-I Collab.)
ATIYA 91 PRL 66 2189 +Chiang, Frank, Haggerty+ (BNL, LANL, PRIN, TRIU)
BEHREND 91 ZPHY C49 401 +Criegee, Field, Franke+ (CELLO Collab.)
CRAWFORD 91 PR D43 46 +Daum, Frosch, Jost, Kettle+ (VILL, VIRG)
LAM 91 PR D44 3345 +Ng (AST)
NATALE 91 PL B258 227 (SPIFT)
AFANASYEV 90 PL B236 116 +Chvyrov, Karpukhin+ (JINR, MOSU, SERP)
Also 90B SJNP 51 664 Afanasyev, Gorchakov, Karpukhin, Komarov+ (JINR)
Translated from YAF 51 1040.
LEE 90 PRL 64 165 +Alliegro, Campagnari+ (BNL, FNAL, VILL, WASH, YALE)
FONVIEILLE 89 PL B233 65 +Bensayah, Berthot, Bertin+ (CLER, LYON, SACL)
NIEBUHR 89 PR D40 2796 +Eichler, Felawka, Kozlowski+ (SINDRUM Collab.)
CAMPAGNARI 88 PRL 61 2062 +Alliegro, Chaloupka+ (BNL, FNAL, PSI, WASH, YALE)
CRAWFORD 88B PL B213 391 +Daum, Frosch, Jost, Kettle, Marshall+ (PSI, VIRG)
DORENBOS... 88 ZPHY C40 497 Dorenbosch, Allaby, Amaldi, Barbiellini+ (CHARM Collab.)
HOFFMAN 88 PL B208 149 (LANL)
MCDONOUGH 88 PR D38 2121 +Highland, McFarlane, Bolton+ (TEMP, LANL, CHIC)
PDG 88 PL B204 Yost, Barnett+ (LBL+)
WILLIAMS 88 PR D38 1365 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
ZEPHAT 87 JPG 13 1375 +Playfer, van Doesburg, Bressani+ (OMICRON Collab.)
BOLOTOV 86C JETPL 43 520 +Gninenko, Dzhilkibaev, Isakov (INRM)
Translated from ZETFP 43 405.
CRAWFORD 86 PRL 56 1043 +Daum, Frosch, Jost, Kettle+ (SIN, VIRG)
ATHERTON 85 PL 158B 81 +Bovet, Coet+ (CERN, ISU, LUND, CURIN, EFI)
HERCZEG 84 PR D29 1954 +Hoffman (LANL)
FRANK 83 PR D28 423 +Hoffman, Mischke, Moir+ (LANL, ARZS)
TUPPER 83 PR D28 2905 +Grose, Samuel (OKSU)
BRYMAN 82 PR D26 2538 (TRIU)
MISCHKE 82 PRL 48 1153 +Frank, Hoffman, Moir, Sarracino+ (LANL, ARZS)
HERCZEG 81 PL 100B 347 +Hoffman (LANL)
SCHARDT 81 PR D23 639 +Frank, Hoffmann, Mischke, Moir+ (ARZS, LANL)
AUERBACH 80 PL 90B 317 +Haik, Highland, McFarlane, Macek+ (TEMP, LASL)
HIGHLAND 80 PRL 44 628 +Auerbach, Haik, McFarlane, Macek+ (TEMP, LASL)
AUERBACH 78 PRL 41 275 +Highland, Johnson+ (TEMP, LASL)
FISCHER 78 PL 73B 359 +Extermann, Guisan, Mermod+ (GEVA, SACL)
FISCHER 78B PL 73B 364 +Extermann, Guisan, Mermod+ (GEVA, SACL)
BROWMAN 74 PRL 33 1400 +Dewire, Gittelman, Hanson+ (CORN, BING)
BELLETTINI 70 NC 66A 243 +Bemporad, Lubelsmey+ (PISA, BONN)
KRYSHKIN 70 JETP 30 1037 +Sterligov, Usov (TMSK)
Translated from ZETF 57 1917.
DEVONS 69 PR 184 1356 +Nemethy, Nissim-Sabat, Capua+ (COLU, ROMA)
VASILEVSKY 66 PL 23 281 +Vishnyakov, Dunaitsev+ (JINR)
DUCLOS 65 PL 19 253 +Freytag, Heintze+ (CERN, HEID)
KUTIN 65 JETPL 2 243 +Petrukhin, Prokoshkin (JINR)
Translated from unknown journal.
CZIRR 63 PR 130 341 (LRL)
SAMIOS 62B PR 126 1844 +Plano, Prodell+ (COLU, BNL)
KOBRAK 61 NC 20 1115 (EFI)
SAMIOS 61 PR 121 275 (COLU, BNL)
BUDAGOV 60 JETP 11 755 +Viktor, Dzhelepov, Ermolov+ (JINR)
Translated from ZETF 38 1047.
JOSEPH 60 NC 16 997 (EFI)

$\boxed{\eta}$

$I^G(J^{PC}) = 0^+(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

η MASS

We no longer use the bubble-chamber measurements from the 1960's, which seem to have been systematically high by about 1 MeV. Some early results have been omitted altogether.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
547.30±0.12 OUR AVERAGE					
547.12±0.06±0.25		KRUSCHE	95D	SPEC	$\gamma p \to \eta p$, threshold
547.30±0.15		PLOUIN	92	SPEC	$d p \to \eta\, {}^3\mathrm{He}$
547.45±0.25		DUANE	74	SPEC	$\pi^- p \to n$ neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •					
548.2 ±0.65		FOSTER	65C	HBC	
549.0 ±0.7	148	FOELSCHE	64	HBC	
548.0 ±1.0	91	ALFF-...	62	HBC	
549.0 ±1.2	53	BASTIEN	62	HBC	

η WIDTH

This is the partial decay rate $\Gamma(\eta \to \gamma\gamma)$ divided by the fitted branching fraction for that mode. See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

VALUE (keV)	*DOCUMENT ID*
1.18±0.11 OUR FIT	Error includes scale factor of 1.8.

η DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Neutral modes			
Γ_1	neutral modes		(71.5 ± 0.6) %	S=1.4
Γ_2	2γ		[a] (39.21 ± 0.34) %	S=1.4
Γ_3	$3\pi^0$		(32.2 ± 0.4) %	S=1.3
Γ_4	$\pi^0 2\gamma$		$(7.1 \pm 1.4) \times 10^{-4}$	
Γ_5	other neutral modes		< 2.8 %	CL=90%
	Charged modes			
Γ_6	charged modes		(28.5 ± 0.6) %	S=1.4
Γ_7	$\pi^+\pi^-\pi^0$		(23.1 ± 0.5) %	S=1.4
Γ_8	$\pi^+\pi^-\gamma$		(4.77 ± 0.13) %	S=1.3
Γ_9	$e^+e^-\gamma$		$(4.9 \pm 1.1) \times 10^{-3}$	
Γ_{10}	$\mu^+\mu^-\gamma$		$(3.1 \pm 0.4) \times 10^{-4}$	
Γ_{11}	e^+e^-		$< 7.7 \times 10^{-5}$	CL=90%
Γ_{12}	$\mu^+\mu^-$		$(5.8 \pm 0.8) \times 10^{-6}$	
Γ_{13}	$\pi^+\pi^-e^+e^-$		$(1.3 {}^{+1.2}_{-0.8}) \times 10^{-3}$	
Γ_{14}	$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$	
Γ_{15}	$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%
Γ_{16}	$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%
	Charge conjugation (*C*), Parity (*P*), Charge conjugation × Parity (*CP*), or Lepton Family number (*LF*) violating modes			
Γ_{17}	$\pi^+\pi^-$	*P,CP*	$< 9 \times 10^{-4}$	CL=90%
Γ_{18}	3γ	*C*	$< 5 \times 10^{-4}$	CL=95%
Γ_{19}	$\pi^0e^+e^-$	*C*	[b] $< 4 \times 10^{-5}$	CL=90%
Γ_{20}	$\pi^0\mu^+\mu^-$	*C*	[b] $< 5 \times 10^{-6}$	CL=90%
Γ_{21}	$\mu^+e^- + \mu^-e^+$	*LF*	$< 6 \times 10^{-6}$	CL=90%

[a] See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

[b] *C* parity forbids this to occur as a single-photon process.

CONSTRAINED FIT INFORMATION

An overall fit to a decay rate and 15 branching ratios uses 40 measurements and one constraint to determine 9 parameters. The overall fit has a $\chi^2 = 31.0$ for 32 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{r|rrrrrrrr}
x_3 & 60 \\
x_4 & 3 & 3 \\
x_7 & -85 & -86 & -5 \\
x_8 & -72 & -73 & -5 & 76 \\
x_9 & -10 & -11 & -1 & -6 & -6 \\
x_{10} & 0 & 0 & 0 & -1 & 0 & 0 \\
x_{13} & -4 & -4 & 0 & -15 & -11 & -2 & 0 \\
\Gamma & -10 & -6 & 0 & 8 & 7 & 1 & 0 & 0 \\
\hline
 & x_2 & x_3 & x_4 & x_7 & x_8 & x_9 & x_{10} & x_{13}
\end{array}$$

	Mode	Rate (keV)	Scale factor
Γ_2	2γ	[a] 0.46 ± 0.04	1.8
Γ_3	$3\pi^0$	0.381 ± 0.035	1.8
Γ_4	$\pi^0 2\gamma$	$(8.4 \pm 1.9) \times 10^{-4}$	1.1
Γ_7	$\pi^+\pi^-\pi^0$	0.274 ± 0.026	1.8
Γ_8	$\pi^+\pi^-\gamma$	0.057 ± 0.005	1.7
Γ_9	$e^+e^-\gamma$	0.0058 ± 0.0014	
Γ_{10}	$\mu^+\mu^-\gamma$	$(3.7 \pm 0.6) \times 10^{-4}$	1.1
Γ_{13}	$\pi^+\pi^-e^+e^-$	$0.0015^{+0.0015}_{-0.0009}$	

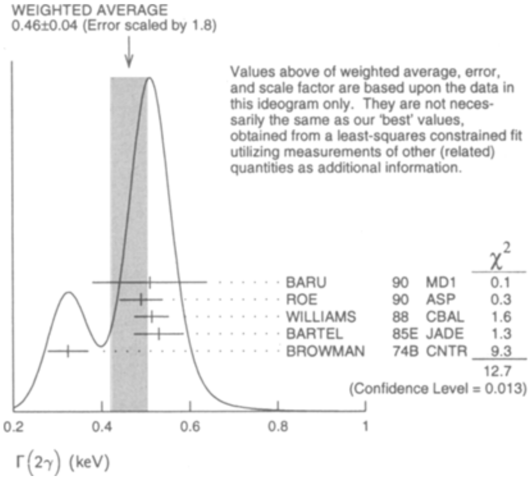
η DECAY RATES

$\Gamma(2\gamma)$ Γ_2

See the table immediately above giving the fitted decay rates. See also the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$," in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
0.46 ±0.04 OUR FIT					Error includes scale factor of 1.8.
0.46 ±0.04 OUR AVERAGE					Error includes scale factor of 1.8. See the ideogram below.
0.51 ±0.12 ±0.05	36	BARU	90	MD1	$e^+e^- \to e^+e^-\eta$
0.490±0.010±0.048	2287	ROE	90	ASP	$e^+e^- \to e^+e^-\eta$
0.514±0.017±0.035	1295	WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-\eta$
0.53 ±0.04 ±0.04		BARTEL	85E	JADE	$e^+e^- \to e^+e^-\eta$
0.324±0.046		BROWMAN	74B	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.64 ±0.14 ±0.13		AIHARA	86	TPC	$e^+e^- \to e^+e^-\eta$
0.56 ±0.16	56	WEINSTEIN	83	CBAL	$e^+e^- \to e^+e^-\eta$
1.00 ±0.22		[1] BEMPORAD	67	CNTR	Primakoff effect

[1] BEMPORAD 67 gives $\Gamma(2\gamma) = 1.21 \pm 0.26$ keV assuming $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.314$. Bemporad private communication gives $\Gamma(2\gamma)^2/\Gamma(\text{total}) = 0.380 \pm 0.083$. We evaluate this using $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.38 \pm 0.01$. Not included in average because the uncertainty resulting from the separation of the coulomb and nuclear amplitudes has apparently been underestimated.



η BRANCHING RATIOS

Neutral modes

$\Gamma(\text{neutral modes})/\Gamma_{\text{total}}$ $\Gamma_1/\Gamma = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.715±0.006 OUR FIT					Error includes scale factor of 1.4.
0.705±0.008	16k	BASILE	71D	CNTR	MM spectrometer
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.79 ±0.08		BUNIATOV	67	OSPK	

$\Gamma(2\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.3921±0.0034 OUR FIT					Error includes scale factor of 1.4.
0.3949±0.0017±0.0030	65k	ABEGG	96	SPEC	$pd \to {}^3\text{He}\eta$

$\Gamma(2\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_2/\Gamma_1 = \Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.5485±0.0022 OUR FIT					Error includes scale factor of 1.1.
0.549 ±0.004 OUR AVERAGE					
0.549 ±0.004		ALDE	84	GAM2	
0.535 ±0.018		BUTTRAM	70	OSPK	
0.59 ±0.033		BUNIATOV	67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.52 ±0.09	88	ABROSIMOV	80	HLBC	
0.60 ±0.14	113	KENDALL	74	OSPK	
0.57 ±0.09		STRUGALSKI	71	HLBC	
0.579 ±0.052		FELDMAN	67	OSPK	
0.416 ±0.044		DIGIUGNO	66	CNTR	Error doubled
0.44 ±0.07		GRUNHAUS	66	OSPK	
0.39 ±0.06		[2] JONES	66	CNTR	

[2] This result from combining cross sections from two different experiments.

$\Gamma(3\pi^0)/\Gamma(\text{neutral modes})$ $\Gamma_3/\Gamma_1 = \Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.4505±0.0022 OUR FIT					Error includes scale factor of 1.1.
0.450 ±0.004 OUR AVERAGE					
0.450 ±0.004		ALDE	84	GAM2	
0.439 ±0.024		BUTTRAM	70	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.44 ±0.08	75	ABROSIMOV	80	HLBC	
0.32 ±0.09		STRUGALSKI	71	HLBC	
0.41 ±0.033		BUNIATOV	67	OSPK	Not indep. of $\Gamma(2\gamma)/\Gamma(\text{neutral modes})$
0.177 ±0.035		FELDMAN	67	OSPK	
0.209 ±0.054		DIGIUGNO	66	CNTR	Error doubled
0.29 ±0.10		GRUNHAUS	66	OSPK	

$\Gamma(3\pi^0)/\Gamma(2\gamma)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.821±0.007 OUR FIT				Error includes scale factor of 1.1.
0.833±0.012 OUR AVERAGE				
0.832±0.005±0.012	KRUSCHE	95D	SPEC	$\gamma p \to \eta p$, threshold
0.841±0.034	AMSLER	93	CBAR	$\bar{p}p \to \pi^+\pi^-\eta$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.822±0.009	[3] ALDE	84	GAM2	
0.91 ±0.14	COX	70B	HBC	
0.75 ±0.09	DEVONS	70	OSPK	
0.88 ±0.16	BALTAY	67D	DBC	
1.1 ±0.2	CENCE	67	OSPK	
1.25 ±0.39	BACCI	63	CNTR	Inverse BR reported

[3] This result is not independent of other ALDE 84 results in this Listing, and so is omitted from the fit and average.

$\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_4/\Gamma_1 = \Gamma_4/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN
(1.00 ±0.20) × 10^{-3} OUR FIT			
0.0010 ±0.0002	ALDE	84	GAM2

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

These results are summarized in the review by LANDSBERG 85.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
7.1±1.4 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
9.5±2.3		70	BINON	82	GAM2	See ALDE 84
<30	90	0	DAVYDOV	81	GAM2	$\pi^- p \to \eta n$

$\Gamma(\text{neutral modes})/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^+\pi^-\gamma)+\Gamma(e^+e^-\gamma)]$ $\Gamma_1/(\Gamma_7+\Gamma_8+\Gamma_9) = (\Gamma_2+\Gamma_3+\Gamma_4)/(\Gamma_7+\Gamma_8+\Gamma_9)$

VALUE	EVTS	DOCUMENT ID		TECN
2.52±0.08 OUR FIT				Error includes scale factor of 1.5.
2.64±0.23		BALTAY	67B	DBC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.5 ±1.0	280	[4] JAMES	66	HBC
3.20±1.26	53	[4] BASTIEN	62	HBC
2.5 ±1.0	10	[4] PICKUP	62	HBC

[4] These experiments are not used in the averages as they do not separate clearly $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ from each other. The reported values thus probably contain some unknown fraction of $\eta \to \pi^+\pi^-\gamma$.

$\Gamma(2\gamma)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^+\pi^-\gamma)+\Gamma(e^+e^-\gamma)]$ $\Gamma_2/(\Gamma_7+\Gamma_8+\Gamma_9)$

VALUE	EVTS	DOCUMENT ID		TECN
1.38±0.04 OUR FIT				Error includes scale factor of 1.5.
1.1 ±0.4 OUR AVERAGE				
1.51±0.93	75	KENDALL	74	OSPK
0.99±0.48		CRAWFORD	63	HBC

$\Gamma(\text{neutral modes})/\Gamma(\pi^+\pi^-\pi^0)$ $\Gamma_1/\Gamma_7 = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma_7$

VALUE	EVTS	DOCUMENT ID		TECN
3.09±0.10 OUR FIT				Error includes scale factor of 1.4.
3.26±0.30 OUR AVERAGE				
2.54±1.89	74	KENDALL	74	OSPK
3.4 ±1.1	29	AGUILAR-...	72B	HBC
2.83±0.80	70	[5] BLOODWO...	72B	HBC
3.6 ±0.6	244	FLATTE	67B	HBC
2.89±0.56		ALFF-...	66	HBC
3.6 ±0.8	50	KRAEMER	64	DBC
3.8 ±1.1		PAULI	64	DBC

[5] Error increased from published value 0.5 by Bloodworth (private communication).

$\Gamma(2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_2/Γ_7

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.70±0.08 OUR FIT					Error includes scale factor of 1.5.
1.75±0.13 OUR AVERAGE					
1.78±0.10±0.13	1077	AMSLER	95	CBAR	$\bar{p}p \to \pi^+\pi^-\eta$ at rest
1.72±0.25	401	BAGLIN	69	HLBC	
1.61±0.39		FOSTER	65	HBC	

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_3/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.39±0.05 OUR FIT Error includes scale factor of 1.4.				
1.34±0.10 OUR AVERAGE Error includes scale factor of 1.2.				
1.44±0.09±0.10	1627	AMSLER 95	CBAR	$\bar{p}p \to \pi^+\pi^-\eta$ at rest
$1.50^{+0.15}_{-0.29}$	199	BAGLIN 69	HLBC	
$1.47^{+0.20}_{-0.17}$		BULLOCK 68	HLBC	
1.3 ±0.4		BAGLIN 67B	HLBC	
0.90±0.24		FOSTER 65	HBC	
2.0 ±1.0		FOELSCHE 64	HBC	
0.83±0.32		CRAWFORD 63	HBC	

$\Gamma(\text{other neutral modes})/\Gamma_{\text{total}}$ — Γ_5/Γ

These are neutral modes other than $\gamma\gamma$, $3\pi^0$, and $\pi^0\gamma\gamma$; nearly any such mode one can think of would violate *P*, or *C*, or both.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.028	90	ABEGG 96	SPEC	$pd \to {}^3\text{He}\eta$

Charged modes

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_8/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN
0.207±0.004 OUR FIT Error includes scale factor of 1.1.			
0.207±0.004 OUR AVERAGE Error includes scale factor of 1.1.			
0.209±0.004	18k	THALER 73	ASPK
0.201±0.006	7250	GORMLEY 70	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.28 ±0.04		BALTAY 67B	DBC
0.25 ±0.035		LITCHFIELD 67	DBC
0.30 ±0.06		CRAWFORD 66	HBC
0.196±0.041		FOSTER 65C	HBC

$\Gamma(e^+e^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_9/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
2.1±0.5 OUR FIT				
2.1±0.5	80	JANE 75B	OSPK	See the erratum

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
3.1±0.4 OUR FIT				
3.1±0.4	600	DZHELYADIN 80	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5±0.75	100	BUSHNIN 78	SPEC	See DZHELYADIN 80

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.77	90	BROWDER 97B	CLE2	$e^+e^- \simeq$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2	90	WHITE 96	SPEC	$pd \to \eta{}^3\text{He}$
<3	90	DAVIES 74	RVUE	Uses ESTEN 67

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
5.8±0.8 OUR AVERAGE					
5.7±0.7±0.5		114	ABEGG 94	SPEC	$pd \to \eta{}^3\text{He}$
6.5±2.1		27	DZHELYADIN 80B	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5.6^{+0.6}_{-0.7}$±0.5		100	KESSLER 93	SPEC	See ABEGG 94
<20	95	0	WEHMANN 68	OSPK	

$\Gamma(\mu^+\mu^-)/\Gamma(2\gamma)$ — Γ_{12}/Γ_2

VALUE (units 10^{-5})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
5.9±2.2	HYAMS 69	OSPK

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma(\pi^+\pi^-\gamma)$ — Γ_{13}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN
$0.026^{+0.026}_{-0.016}$ OUR FIT			
0.026±0.026	1	GROSSMAN 66	HBC

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN
$0.13^{+0.12}_{-0.08}$ OUR FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •		
<0.7	RITTENBERG 65	HBC

$\Gamma(\pi^+\pi^-2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{14}/Γ_7

VALUE	CL%	DOCUMENT ID	TECN
<0.009		PRICE 67	HBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.016	95	BALTAY 67B	DBC

$\Gamma(\pi^+\pi^-\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{15}/Γ_7

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
<0.24	90	0	THALER 73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	90		ARNOLD 68	HLBC
<1.6	95		BALTAY 67B	DBC
<7.0			FLATTE 67	HBC
<0.9			PRICE 67	HBC

$\Gamma(\pi^0\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<3	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$

Rare or forbidden modes

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

Forbidden by *P* and *CP* invariance.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 9	90		AKHMETSHIN 97C	CMD2	$e^+e^- \to \pi^+\pi^-\gamma$, 0.99–1.04 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<15		0	THALER 73	ASPK	

$\Gamma(3\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_{18}/\Gamma_1 = \Gamma_{18}/(\Gamma_2+\Gamma_3+\Gamma_4)$

Forbidden by *C* invariance.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<7	95	ALDE 84	GAM2

$\Gamma(\pi^0e^+e^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{19}/Γ_7

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN
< 1.9	90		JANE 75	OSPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 42	90		BAGLIN 67	HLBC
< 16	90	0	BILLING 67	HLBC
< 77		0	FOSTER 65B	HBC
<110			PRICE 65	HBC

$\Gamma(\pi^0e^+e^-)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.016	90	0	MARTYNOV 76	HLBC
<0.084	90		BAZIN 68	DBC
<0.7			RITTENBERG 65	HBC

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{20}/Γ

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5		WEHMANN 68	OSPK	

$[\Gamma(\mu^+e^-)+\Gamma(\mu^-e^+)]/\Gamma_{\text{total}}$ — Γ_{21}/Γ

Forbiden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<6	90	WHITE 96	SPEC	$pd \to \eta{}^3\text{He}$

η C-NONCONSERVING DECAY PARAMETERS

$\pi^+\pi^-\pi^0$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error > 1.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
0.09±0.17 OUR AVERAGE			
0.28±0.26	165k	JANE 74	OSPK
−0.05±0.22	220k	LAYTER 72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.5 ±0.5	37k	[6] GORMLEY 68C	ASPK

[6] The GORMLEY 68C asymmetry is probably due to unmeasured (**E** × **B**) spark chamber effects. New experiments with (**E** × **B**) controls don't observe an asymmetry.

$\pi^+\pi^-\pi^0$ SEXTANT ASYMMETRY PARAMETER

Measurements with an error > 2.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
0.18±0.16 OUR AVERAGE			
0.20±0.25	165k	JANE 74	OSPK
0.10±0.22	220k	LAYTER 72	ASPK
0.5 ±0.5	37k	GORMLEY 68C	WIRE

$\pi^+\pi^-\pi^0$ QUADRANT ASYMMETRY PARAMETER

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
−0.17±0.17 OUR AVERAGE			
−0.30±0.25	165k	JANE 74	OSPK
−0.07±0.22	220k	LAYTER 72	ASPK

$\pi^+\pi^-\gamma$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error > 2.0×10^{-2} have been omitted.

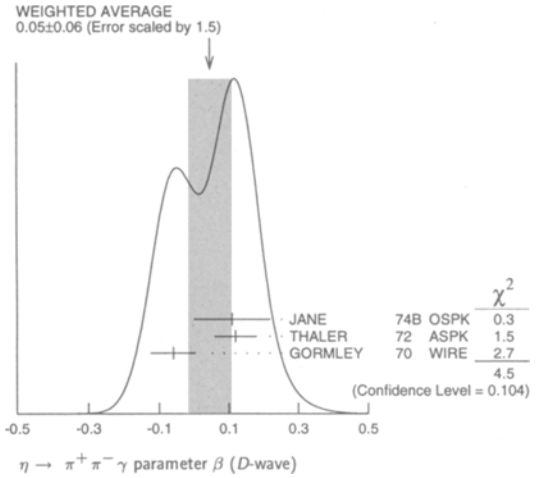
VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.9 ±0.4 OUR AVERAGE				
1.2 ±0.6	35k	JANE	74B	OSPK
0.5 ±0.6	36k	THALER	72	ASPK
1.22±1.56	7257	GORMLEY	70	ASPK

$\pi^+\pi^-\gamma$ PARAMETER β (*D*-wave)

Sensitive to a *D*-wave contribution: $dN/d\cos\theta = \sin^2\theta\ (1 + \beta\ \cos^2\theta)$

VALUE	EVTS	DOCUMENT ID		TECN
0.05 ±0.06 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.			
0.11 ±0.11	35k	JANE	74B	OSPK
0.12 ±0.06		[7] THALER	72	ASPK
−0.060±0.065	7250	GORMLEY	70	WIRE

[7] The authors don't believe this indicates *D*-wave because the dependence of β on the γ energy is inconsistent with theoretical prediction. A $\cos^2\theta$ dependence may also come from *P*- and *F*-wave interference.



ENERGY DEPENDENCE OF $\eta \to 3\pi$ DALITZ PLOTS

PARAMETERS FOR $\eta \to \pi^+\pi^-\pi^0$

See the "Note on η Decay Parameters" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1454. The following experiments fit to one or more of the coefficients *a*, *b*, *c*, *d*, or *e* for $|\text{matrix element}|^2 = 1 + ay + by^2 + cx + dx^2 + exy$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	3230	[8] ABELE	98D	CBAR	$\overline{p}p \to \pi^0\pi^0\eta$ at rest
	1077	[9] AMSLER	95	CBAR	$\overline{p}p \to \pi^+\pi^-\eta$ at rest
	81k	LAYTER	73	ASPK	
	220k	LAYTER	72	ASPK	
	1138	CARPENTER	70	HBC	
	349	DANBURG	70	DBC	
	7250	GORMLEY	70	WIRE	
	526	BAGLIN	69	HLBC	
	7170	CNOPS	68	OSPK	
	37k	GORMLEY	68C	WIRE	
	1300	CLPWY	66	HBC	
	705	LARRIBE	66	HBC	

[8] ABELE 98D obtain $a = -1.22 \pm 0.07$ and $b = 0.22 \pm 0.11$ when *c* (our *d*) is fixed at 0.06.

[9] AMSLER 95 fits to $(1+ay+by^2)$ and obtains $a{=}-0.94 \pm 0.15$ and $b{=}0.11 \pm 0.27$.

α PARAMETER FOR $\eta \to 3\pi^0$

See the "Note on η Decay Parameters" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1454. The value here is of α in $|\text{matrix element}|^2 = 1 + 2\alpha z$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.039±0.015 OUR AVERAGE					
−0.052±0.017±0.010	98k	ABELE	98C	CBAR	$\overline{p}p \to 5\pi^0$
−0.022±0.023	50k	ALDE	84	GAM2	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.32 ±0.37	192	BAGLIN	70	HLBC	

η REFERENCES

ABELE	98C	PL B417 193	+Adomeit+	(CERN Crystal Barrel Collab.)
ABELE	98D	PL B417 197	+Adomeit+	(CERN Crystal Barrel Collab.)
AKHMETSHIN	97C	PL B415 452	+Aksenov+	(NOVO, BOST, PITT, YALE)
BROWDER	97B	PR D56 5359	+Li, Li, Rodriguez+	(CLEO Collab.)
ABEGG	96	PR D53 11	+Abela, Boudard+	(Saturne SPES2 Collab.)
WHITE	96	PR D53 6658	+Tippens, Abegg+	(Saturne SPES2 Collab.)
AMSLER	95	PL B346 203	+Armstrong, Heinsius+	(Crystal Barrel Collab.)
KRUSCHE	95D	ZPHY A351 237	+Ahrens+	(TAPS + A2 Collab.)
ABEGG	94	PR D50 92	+Baldisseri, Boudard+	(Saturne SPES2 Collab.)
AMSLER	93	ZPHY C58 175	+Armstrong, Merkel+	(Crystal Barrel Collab.)
KESSLER	93	PRL 70 892	+Abegg, Baldisseri+	(Saturne SPES2 Collab.)
PLOUIN	92	PL B276 526	+Fleury+	(Saturne SPES4 Collab.)
BARU	90	ZPHY C48 581	+Blinov, Blinov+	(MD-1 Collab.)
ROE	90	PR D41 17	+Bartha, Burke, Garbincius+	(ASP Collab.)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
AIHARA	86	PR D33 844	+Alston-Garnjost+	(TPC-2γ Collab.)
BARTEL	85E	PL 160B 421	+Becker, Cords, Felst+	(JADE Collab.)
LANDSBERG	85	PRPL 128 310		(SERP)
ALDE	84	ZPHY C25 225	+Binon, Bricman, Donskov+	(SERP, BELG, LAPP)
Also	84B	SJNP 40 918	Alde, Binon, Bricman+	(SERP, BELG, LAPP)
		Translated from YAF 40 1447.		
WEINSTEIN	83	PR D28 2896	+Antreasyan, Gu, Kollman+	(Crystal Ball Collab.)
BINON	82	SJNP 36 391	+Bricman, Gouanere+	(SERP, BELG, LAPP, CERN)
		Translated from YAF 36 670.		
Also	82B	NC 71A 497	Binon, Bricman+	(SERP, BELG, LAPP, CERN)
DAVYDOV	81	LNC 32 45	+Donskov, Inyakin+	(SERP, BELG, LAPP, CERN)
Also	81B	SJNP 33 825	Davydov, Binon+	(SERP, BELG, LAPP, CERN)
		Translated from YAF 33 1534.		
DZHELYADIN	81	PL 105B 239	+Golovkin, Konstantinov, Kubarovski+	(SERP)
Also	81C	SJNP 33 822	Dzhelyadin, Viktorov, Golovkin+	(SERP)
		Translated from YAF 33 1529.		
ABROSIMOV	80	SJNP 31 195	+Ilina, Niszcz, Okhrimenko+	(JINR)
		Translated from YAF 31 371.		
DZHELYADIN	80	PL 94B 548	+Viktorov, Golovkin+	(SERP)
Also	80C	SJNP 32 516	Dzhelyadin, Golovkin, Kachanov+	(SERP)
		Translated from YAF 32 998.		
DZHELYADIN	80B	PL 97B 471	+Viktorov, Golovkin+	(SERP)
Also	80D	SJNP 32 518	Dzhelyadin, Golovkin, Kachanov+	(SERP)
		Translated from YAF 32 1002.		
BUSHNIN	78	PL 79B 147	+Dzhelyadin, Golovkin, Gritsuk+	(SERP)
Also	78B	SJNP 28 775	Bushnin, Golovkin, Gritsuk, Dzhelyadin+	(SERP)
		Translated from YAF 28 1507.		
MARTYNOV	76	SJNP 23 48	+Saltykov, Tarasov, Uzhinskii	(JINR)
		Translated from YAF 23 93.		
JANE	75	PL 59B 99	+Grannis, Jones, Lipman, Owen+	(RHEL, LOWC)
JANE	75B	PL 59B 103	+Grannis, Jones, Lipman, Owen+	(RHEL, LOWC)
Also	78B	PL 73B 503	Jane	
Erratum in private communication.				
BROWMAN	74B	PRL 32 1067	+Dewire, Gittelman, Hanson, Loh+	(CORN, BING)
DAVIES	74	NC 24A 324	+Guy, Zia	(BIRM, RHEL, SHMP)
DUANE	74	PRL 32 425	+Binnie, Camilleri, Carr+	(LOIC, SHMP)
JANE	74	PL 48B 260	+Jones, Lipman, Owen+	(RHEL, LOWC, SUSS)
JANE	74B	PL 48B 265	+Jones, Lipman, Owen+	(RHEL, LOWC, SUSS)
KENDALL	74	NC 21A 387	+Lanou, Massimo, Shapiro+	(BROW, BARI, MIT)
LAYTER	73	PR D7 2565	+Appel, Kotlewski, Lee, Stein, Thaler	(COLU)
THALER	73	PR D7 2569	+Appel, Kotlewski, Layter, Lee, Stein	(COLU)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
BLOODWO...	72B	NP B39 525	Bloodworth, Jackson, Prentice, Yoon	(TNTO)
LAYTER	72	PRL 29 316	+Appel, Kotlewski, Lee, Stein, Thaler	(COLU)
THALER	72	PRL 29 313	+Appel, Kotlewski, Layter, Lee, Stein	(COLU)
BASILE	71D	NC 3A 796	+Bollini, Dalpiaz, Frabetti+	(CERN, BGNA, STRB)
STRUGALSKI	71	NP B27 429	+Chuvilo, Gemesy, Ivanovskaya+	(JINR)
BAGLIN	70	NP B22 66	+Bezaguet, Degrange+	(EPOL, MADR, STRB)
BUTTRAM	70	PRL 25 1358	+Kreisler, Mischke	(PRIN)
CARPENTER	70	PR D1 1303	+Binkley, Chapman, Cox, Dagan+	(DUKE)
COX	70B	PRL 24 534	+Fortney, Golson	(DUKE)
DANBURG	70	PR D2 2564	+Abolins, Dahl, Davies, Hoch, Kirz+	(LRL)
DEVONS	70	PR D1 1936	+Grunhaus, Kozlowski, Nemethy+	(COLU, SYRA)
GORMLEY	70	PR D2 501	+Hyman, Lee, Nash, Peoples+	(COLU, BNL)
Also	70B	Thesis Nevis 181	Gormley	(COLU)
BAGLIN	69	PL 29B 445	+Bezaguet+	(EPOL, UCB, MADR, STRB)
Also	70	NP B22 66	Baglin, Bezaguet, Degrange+	(EPOL, MADR, STRB)
HYAMS	69	PL 29B 128	+Koch, Potter, VonLindern+	(CERN, MPIM)
ARNOLD	68	PL 27B 466	+Paty, Baglin, Bingham+	(STRB, MADR, EPOL, UCB)
BAZIN	68	PRL 20 895	+Goshaw, Zacher+	(PRIN, QUKI)
BULLOCK	68	PL 27B 402	+Esten, Fleming, Govan, Henderson+	(LOUC)
CNOPS	68	PRL 21 1609	+Hough, Cohn+	(BNL, ORNL, UCND, TENN, PENN)
GORMLEY	68C	PRL 21 402	+Hyman, Lee, Nash, Peoples+	(COLU, BNL)
WEHMANN	68	PRL 20 748	+Engels+	(HARV, CASE, SLAC, CORN, MCGI)
BAGLIN	67	PL 24B 637	+Bezaguet, Degrange+	(EPOL, UCB)
BAGLIN	67B	BAPS 12 567	+Bezaguet, Degrange+	(EPOL, UCB)
BALTAY	67B	PRL 19 1498	+Franzini, Kim, Newman+	(COLU, STON)
BALTAY	67D	PRL 19 1495	+Franzini, Kim, Newman+	(COLU, BRAN)
BEMPORAD	67	PL 25B 380	+Braccini, Foa, Lubelsmey+	(PISA, BONN)
Also	67	Private Comm.	Ion	
BILLING	67	PL 25B 435	+Bullock, Esten, Govan+	(LOUC, OXF)
BUNIATOV	67	PL 25B 560	+Zavattini, Deinet+	(CERN, KARL)
CENCE	67	PRL 19 1393	+Peterson, Stenger, Chiu+	(HAWA, LRL)
ESTEN	67	PL 24B 115	+Govan, Knight, Miller, Tovey+	(LOUC, OXF)
FELDMAN	67	PRL 18 868	+Frati, Gleeson, Halpern+	(PENN)
FLATTE	67	PRL 18 976		(LRL)
FLATTE	67B	PR 163 1441	+Wohl	(LRL)
LITCHFIELD	67	PL 24B 486	+Rangan, Segar, Smith+	(RHEL, SACL)
PRICE	67	PRL 18 1207	+Crawford	(LRL)
ALFF-...	66	PR 145 1072	Alff-Steinberger, Berley+	(COLU, RUTG)
CLPWY	66	PR 149 1044		(SCUC, LRL, PURD, WISC, YALE)
CRAWFORD	66	PRL 16 333	+Price	(LRL)
DIGIUGNO	66	PRL 16 767	+Giorgi, Silvestri+	(NAPL, TRST, FRAS)
GROSSMAN	66	PR 146 993	+Price, Crawford	(LRL)
GRUNHAUS	66	Thesis		(COLU)
JAMES	66	PR 142 896	+Kraybill	(YALE, BNL)
JONES	66	PL 23 597	+Binnie, Duane, Horsey, Mason+	(LOIC, RHEL)
LARRIBE	66	PL 23 600	+Leveque, Muller, Pauli+	(SACL, RHEL)
FOSTER	65	PR 138B 652	+Peters, Meer, Loeffler+	(WISC, PURD)
FOSTER	65B	Athens Conf.	+Good, Meer	(WISC)
FOSTER	65C	Thesis		(WISC)
PRICE	65	PRL 15 123	+Crawford	(LRL)
RITTENBERG	65	PRL 15 556	+Kalbfleisch	(LRL, BNL)
FOELSCHE	64	PR 134B 1138	+Kraybill	(YALE)
KRAEMER	64	PR 136B 496	+Madansky, Fields+	(JHU, NWES, WOOD)
PAULI	64	PL 13 351	+Muller	(SACL)
BACCI	63	PRL 11 37	+Penso, Salvini+	(ROMA, FRAS)
CRAWFORD	63	PRL 10 546	+Lloyd, Fowler	(LRL, DUKE)
Also	66B	PRL 16 907	Crawford, Lloyd, Fowler	(LRL, DUKE)
ALFF-...	62	PRL 9 322	Alff-Steinberger, Berley, Colley+	(COLU, RUTG)
BASTIEN	62	PRL 8 114	+Berge, Dahl, Ferro-Luzzi+	(LRL)
PICKUP	62	PRL 8 329	+Robinson, Salant	(CNRC, BNL)

$f_0(400–1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

$f_0(400–1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
(400–1200)–i(300–500) OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$469.5 - i178.6$	[1] OLLER	97	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$470 - i250$	[2,3] TORNQVIST	96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
$\sim (1100 - i300)$	AMSLER	95B	CBAR	$\overline{p}p \to 3\pi^0$
$400 - i500$	[3,4] AMSLER	95D	CBAR	$\overline{p}p \to 3\pi^0$
$1100 - i137$	[3,5] AMSLER	95D	CBAR	$\overline{p}p \to 3\pi^0$
$387 - i305$	[3,6] JANSSEN	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$525 - i269$	[7] ACHASOV	94	RVUE	$\pi\pi \to \pi\pi$
$370 - i356$	[8] ZOU	94B	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$408 - i342$	[3,8] ZOU	93	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$870 - i370$	[3,9] AU	87	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$750 \pm 50 - i(450 \pm 50)$	[10] ESTABROOKS	79	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$660 \pm 100 - i(320 \pm 70)$	PROTOPOP...	73	HBC	$\pi\pi \to \pi\pi, K\overline{K}$
$650 - i370$	[11] BASDEVANT	72	RVUE	$\pi\pi \to \pi\pi$

[1] Coupled channel analysis combined with chiral perturbation theory.

[2] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

[3] Demonstrates explicitly that $f_0(400–1200)$ and $f_0(1370)$ are two different poles.

[4] Coupled channel analysis of $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$ and $\pi^0\pi^0\eta$ on sheet II.

[5] Coupled channel analysis of $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$ and $\pi^0\pi^0\eta$ on sheet III.

[6] Analysis of data from FALVARD 88.

[7] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.

[8] Analysis of data from OCHS 73, GRAYER 74, and ROSSELET 77.

[9] Analysis of data from OCHS 73, GRAYER 74, BECKER 79, and CASON 83.

[10] Analysis of data from APEL 73, GRAYER 74, CASON 76, PAWLICKI 77. Includes spread and errors of 4 solutions.

[11] Analysis of data from BATON 70, BENSINGER 71, COLTON 71, BAILLON 72, PROTOPOPESCU 73, and WALKER 67.

$f_0(400–1200)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETERS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
(400–1200) OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
780 ±30	ALDE	97	GAM2	$450\ pp \to pp\pi^0\pi^0$
553.3± 0.5	[12] ISHIDA	96	RVUE	$\pi\pi \to \pi\pi$
761 ±12	[13] SVEC	96	RVUE	$6–17\ \pi N_{\mathrm{polar}} \to \pi^+\pi^-N$
~ 860	[14] TORNQVIST	96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
1165 ±50	[15,16] ANISOVICH	95	RVUE	$\pi^-p \to \pi^0\pi^0n$, $\overline{p}p \to \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$
~ 1000	[17] ACHASOV	94	RVUE	$\pi\pi \to \pi\pi$
506 ±10	KAMINSKI	94	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
414 ±20	[13] AUGUSTIN	89	DM2	

[12] Reanalysis of data from HYAMS 73, GRAYER 74, SRINIVASAN 75, and ROSSELET 77 using the interfering amplitude method.

[13] Breit-Wigner fit to S-wave intensity measured in $\pi N \to \pi^-\pi^+N$ on polarized targets. The fit does not include $f_0(980)$.

[14] Uses data from ASTON 88, OCHS 73, HYAMS 73, ARMSTRONG 91B, GRAYER 74, CASON 83, ROSSELET 77, and BEIER 72B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

[15] Uses $\pi^0\pi^0$ data from ANISOVICH 94, AMSLER 94D, and ALDE 95B, $\pi^+\pi^-$ data from OCHS 73, GRAYER 74 and ROSSELET 77, and $\eta\eta$ data fromANISOVICH 94.

[16] The pole is on Sheet III. Demonstrates explicitly that $f_0(400–1200)$ and $f_0(1370)$ are two different poles.

[17] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.

$f_0(400–1200)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
(600–1000) OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
780 ±60	ALDE	97	GAM2	$450\ pp \to pp\pi^0\pi^0$
242.6± 1.2	[18] ISHIDA	96	RVUE	$\pi\pi \to \pi\pi$
290 ±54	[19] SVEC	96	RVUE	$6–17\ \pi N_{\mathrm{polar}} \to \pi^+\pi^-N$
~ 880	[20] TORNQVIST	96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
460 ±40	[21,22] ANISOVICH	95	RVUE	$\pi^-p \to \pi^0\pi^0n$, $\overline{p}p \to \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$
~ 3200	[23] ACHASOV	94	RVUE	$\pi\pi \to \pi\pi$
494 ± 5	KAMINSKI	94	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
494 ±58	[19] AUGUSTIN	89	DM2	

[18] Reanalysis of data from HYAMS 73, GRAYER 74, SRINIVASAN 75, and ROSSELET 77 using the interfering amplitude method.

[19] Breit-Wigner fit to S-wave intensity measured in $\pi N \to \pi^-\pi^+N$ on polarized targets. The fit does not include $f_0(980)$.

[20] Uses data from ASTON 88, OCHS 73, HYAMS 73, ARMSTRONG 91B, GRAYER 74, CASON 83, ROSSELET 77, and BEIER 72B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

[21] Uses $\pi^0\pi^0$ data from ANISOVICH 94, AMSLER 94D, and ALDE 95B, $\pi^+\pi^-$ data from OCHS 73, GRAYER 74 and ROSSELET 77, and $\eta\eta$ data fromANISOVICH 94.

[22] The pole is on Sheet III. Demonstrates explicitly that $f_0(400–1200)$ and $f_0(1370)$ are two different poles.

[23] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.

$f_0(400–1200)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	dominant
Γ_2	$\gamma\gamma$	seen

$f_0(400–1200)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_2

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	[24] MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10±6	COURAU	86	DM1	$e^+e^- \to \pi^+\pi^-e^+e^-$

[24] Analysis of data from BOYER 90 and MARSISKE 90.

$f_0(400–1200)$ REFERENCES

ALDE	97	PL B397 350	+Bellazzini, Binon+	(GAMS Collab.)
OLLER	97	NP A620 438	J.A. Oller+	(VALE)
ISHIDA	96	PTP 95 745	S. Ishida+	(TOKY, MIYA, KEK)
SVEC	96	PR D53 2343		(MCGI)
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
ALDE	95B	ZPHY C66 375	+Binon, Boutemeur+	(GAMS Collab.)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	95	PL B355 363	+Kondashov+	(PNPI, SERP)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
ACHASOV	94	PR D49 5779	+Shestakov	(NOVM)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	94	PL B323 233	+Armstrong+	(Crystal Barrel Collab.)
KAMINSKI	94	PR D50 3145	R. Kaminski+	(CRAC, IPN)
ZOU	94B	PR D50 591	+Bugg	(LOQM)
ZOU	93	PR D48 R3948	+Bugg	(LOQM)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
COURAU	86	NP B271 1	+Falvard, Haissinski, Jousset, Michel+	(CLER, LALO)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
MUKHIN	80	JETPL 32 601 Translated from ZETFP 32 616.	+Patarakin+	(KIAE)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
ESTABROOKS	79	PR D19 2678		(CARL)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL) IJ
ROSSELET	77	PR D15 574	+Extermann, Fischer, Guisan+	(GEVA, SACL)
CASON	76	PRL 36 1485	+Polychronakos, Bishop, Biswas+	(NDAM, ANL) IJ
ESTABROOKS	75	NP B95 322	+Martin	(DURH)
SRINIVASAN	75	PR D12 681	+Helland, Lennox, Klem+	(NDAM, ANL)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
APEL	73	PL 41B 542	+Auslander, Muller+	(KARL, PISA)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
OCHS	73	Thesis		(MPIM, MUNI)
PROTOPOP...	73	PR D7 1279	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)
BAILLON	72	PL 38B 555	+Carnegie, Kluge, Leith, Lynch, Ratcliff+	(SLAC)
BASDEVANT	72	PL 41B 178	+Froggatt, Petersen	(CERN)
BEIER	72B	PRL 29 511	+Buchholtz, Mann+	(PENN)
BENSINGER	71	PL 36B 134	+Erwin, Thompson, Walker	(WISC)
COLTON	71	PR D3 2028	+Malamud, Schlein+	(LBL, FNAL, UCLA, HAWA)
BATON	70	PL 33B 528	+Laurens, Reignier	(SACL)
WALKER	67	RMP 39 695		(WISC)

OTHER RELATED PAPERS

ABELE	98	PR D57 3860	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
ANISOVICH	97	PL B395 123	+Sarantsev	(PNPI)
ANISOVICH	97B	ZPHY A357 123	A.V. Anisovich+	(PNPI)
ANISOVICH	97C	PL B413 137		
ANISOVICH	97D	ZPHY A359 173		
CLOSE	97B	PR D55 5749	F. Close+	(RAL, RUTG, BEIJT)
KAMINSKI	97	ZPHY C74 79	R. Kaminski+	(CRAC)
MALTMAN	97	PL B393 19	K. Maltman, Wolfe	(YORKC)
OLLER	97	NP A620 438	J.A. Oller+	(VALE)
SVEC	97	PR D55 4355	M. Svec	
SVEC	97B	PR D55 5727	M. Svec	(MCGI)
ABELE	96	PL B380 453	+Adomeit, Amsler+	(Crystal Barrel Collab.)
AMSLER	96	PR D53 295	+Close	(ZURI, RAL)
BIJNENS	96	PL B374 210	J. Bijnens, Colangelo, Ecker+	(NORD, BERN, WIEN, HELS)
BONUTTI	96	PRL 77 603	+Amerini, Fragiacomo+	(TRSTI, TRSTT, TRIU)
BUGG	96	NP B471 59	+Sarantsev, Zou	(LOQM, PNPI)
HARADA	96	PR D54 1991	M. Harasa+	(SYRA)
ISHIDA	96	PTP 95 745	S. Ishida+	(TOKY, MIYA, KEK)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
AMSLER	95F	PL B358 389	+Armstrong, Urner+	(Crystal Barrel Collab.)
ANTINORI	95	PL B353 589	+Barberis, Bayes+	(ATHU, BARI, BIRM, CERN, JINR)
BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
GASPERO	95	NP A588 861		(ROMA)
TORNQVIST	95	ZPHY C68 647		(HELS)
AMSLER	94	PL B322 431	+Armstrong, Meyer+	(Crystal Barrel Collab.)
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
KAMINSKI	94	PR D50 3145	R. Kaminski+	(CRAC, IPN)
ADAMO	93	NP A558 13C	+Agnello+	(OBELIX Collab.)

GASPERO	93	NP A562 407		(ROMAI)
MORGAN	93	PR D48 1185	+Pennington	(RAL, DURH)
Also	93C	NC A Conf. Suppl.	Morgan	(RAL)
BOLTON	92B	PRL 69 1328	+Brown, Bunnell+	(Mark III Collab.)
SVEC	92	PR D45 55	+de Lesquen, van Rossum	(MCGI, SACL)
SVEC	92B	PR D45 1518	+de Lesquen, van Rossum	(MCGI, SACL)
SVEC	92C	PR D46 949	+de Lesquen, van Rossum	(MCGI, SACL)
RIGGENBACH	91	PR D43 127	C. Riggenbach, Gasser+	(BERN, CERN, MASA)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
WEINSTEIN	90	PR D41 2236	+Isgur	(TNTO)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
BEVEREN	86	ZPHY C30 615	E. van Beveren+	(NIJM, BIEL)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
ACHASOV	84	ZPHY C22 53	+Devyanin, Shestakov	(NOVM)
GASSER	84	ANP 158 142		
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
TORNQVIST	82	PRL 49 624		(HELS)
COHEN	80	PR D22 2595	+Ayres, Diebold, Kramer, Pawlicki+	(ANL) IJP
COSTA	80	NP B175 402	G. Costa+(BARI, BONN, CERN, GLAS, LIVP, MILA, WIEN)	
BECKER	79B	NP B150 301	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
NAGELS	79	PR D20 1633	+Rijken, Deswart	(NIJM)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL) IJP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
JAFFE	77	PR D15 267,281		(MIT)
FLATTE	76	PL 63B 224		(CERN)
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)

$\rho(770)$

$I^G(J^{PC}) = 1^+(1^{--})$

THE $\rho(770)$

Written February 1998 by S. Eidelman (Novosibirsk).

Determination of the parameters of the $\rho(770)$ is beset with many difficulties because of its large width. In physical region fits, the line shape does not correspond to a relativistic Breit-Wigner function with a P-wave width, but requires some additional shape parameter. This dependence on parametrization was demonstrated long ago by PISUT 68. Bose-Einstein correlations are another source of shifts in the $\rho(770)$ line shape, particularly in the multiparticle final state systems (LAFFERTY 93).

The same model dependence afflicts any other source of the resonance parameters, such as the energy dependence of the phase shift δ_1^1 or the pole position. It is therefore not surprising that a study of $\rho(770)$ dominance in the decays of the η and η' reveals the need for specific dynamical effects in addition to the $\rho(770)$ pole (BENAYOUN 93, ABELE 97B). Recently BENAYOUN 98 compared the predictions of different Vector Meson Dominance (VMD) based models with the data on the $e^+e^- \to \pi^+\pi^-$ cross section below 1 GeV as well as with the phase and near-threshold behaviour of the timelike pion form factor. They showed that only the model based on a hidden local symmetry (HLS) is able to account consistently for all low-energy information, if one also requires a point-like coupling $\gamma\pi^+\pi^-$ which is excluded by common VMD but predicted by HLS.

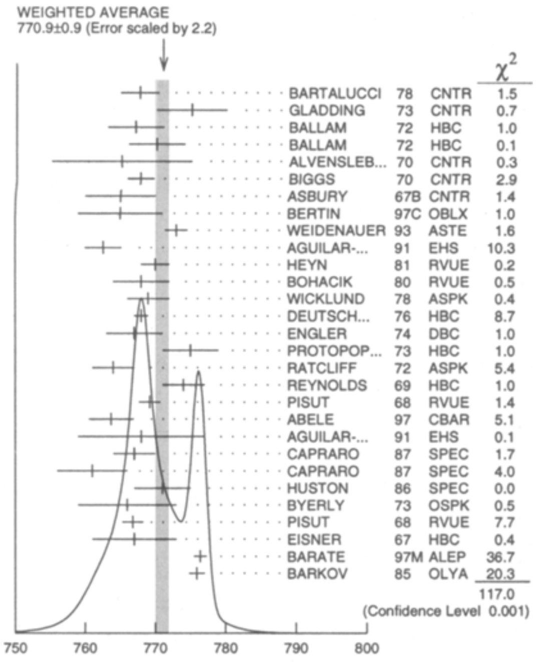
The cleanest determination of the $\rho(770)$ mass and width comes from the e^+e^- annihilation and τ-lepton decays. BARATE 97M showed that the charged $\rho(770)$ parameters measured from τ-lepton decays are consistent with those of the neutral one determined from e^+e^- data of BARKOV 85.

$\rho(770)$ MASS

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
770.0±0.8 OUR AVERAGE	Includes data from the 4 datablocks that follow this one. Error includes scale factor of 1.8. See the ideogram below.



$\rho(770)$ MASS MIXED CHARGES

MIXED CHARGES, τ DECAYS and e^+e^-

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
776.0±0.9 OUR AVERAGE				
776.4±0.9±1.5	[1] BARATE 97M	ALEP		$\tau^- \to \pi^-\pi^0\nu_\tau$
775.9±1.1	[2] BARKOV 85	OLYA	0	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
775.1±0.7	[3] BENAYOUN 98	RVUE		$e^+e^- \to \pi^+\pi^-$, $\mu^+\mu^-$
764.1±0.7	[4] O'CONNELL 97	RVUE		$e^+e^- \to \pi^+\pi^-$
757.5±1.5	[5] BERNICHA 94	RVUE		$e^+e^- \to \pi^+\pi^-$
768 ±1	[6] GESHKEN... 89	RVUE		$e^+e^- \to \pi^+\pi^-$

CHARGED ONLY, HADROPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
766.5±1.1 OUR AVERAGE					
763.7±3.2		ABELE 97	CBAR		$\bar{p}n \to \pi^-\pi^0\pi^0$
768 ±9		AGUILAR-... 91	EHS		400 pp
767 ±3	2935	[7] CAPRARO 87	SPEC	−	200 π^-Cu $\to \pi^-\pi^0$Cu
761 ±5	967	[7] CAPRARO 87	SPEC	−	200 π^-Pb $\to \pi^-\pi^0$Pb
771 ±4		HUSTON 86	SPEC	+	202 π^+A $\to \pi^+\pi^0$A
766 ±7	6500	[8] BYERLY 73	OSPK	−	5 π^-p
766.8±1.5	9650	[9] PISUT 68	RVUE	−	1.7–3.2 π^-p, t <10
767 ±6	900	[7] EISNER 67	HBC	−	4.2 π^-p, t <10

NEUTRAL ONLY, PHOTOPRODUCED

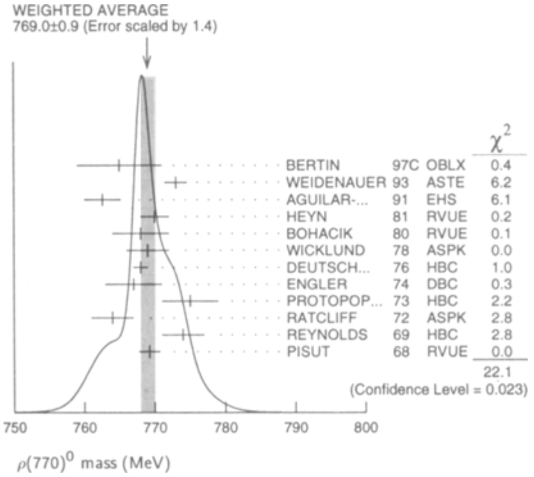
The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
768.1± 1.3 OUR AVERAGE					
767.6± 2.7		BARTALUCCI 78	CNTR	0	$\gamma p \to e^+e^-p$
775 ± 5		GLADDING 73	CNTR	0	2.9–4.7 γp
767 ± 4	1930	BALLAM 72	HBC	0	2.8 γp
770 ± 4	2430	BALLAM 72	HBC	0	4.7 γp
765 ±10		ALVENSLEB... 70	CNTR	0	γA, t <0.01
767.7± 1.9	140k	BIGGS 70	CNTR	0	<4.1 γC $\to \pi^+\pi^-$C
765 ± 5	4000	ASBURY 67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
769.0±0.9 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.				
765 ±6		BERTIN	97C	OBLX		0.0 $\overline{p}p \to \pi^+\pi^-\pi^0$
773 ±1.6		WEIDENAUER	93	ASTE		$\overline{p}p \to \pi^+\pi^-\omega$
762.6±2.6		AGUILAR-...	91	EHS		400 pp
770 ±2		[10] HEYN	81	RVUE		Pion form factor
768 ±4		[11,12] BOHACIK	80	RVUE	0	
769 ±3		[8] WICKLUND	78	ASPK	0	3,4,6 $\pi^\pm N$
768 ±1	76000	DEUTSCH...	76	HBC	0	16 $\pi^+ p$
767 ±4	4100	ENGLER	74	DBC	0	6 $\pi^+ n \to \pi^+\pi^- p$
775 ±4	32000	[11] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, $t<0.4$
764 ±3	6800	RATCLIFF	72	ASPK	0	15 $\pi^- p$, $t<0.3$
774 ±3	1700	REYNOLDS	69	HBC	0	2.26 $\pi^- p$
769.2±1.5	13300	[13] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, $t<10$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
777 ±2	4943	[14] ADAMS	97	E665		470 $\mu p \to \mu X B$
770 ±2		[15] BOGOLYUB...	97	MIRA		32 $\overline{p}p \to \pi^+\pi^- X$
768 ±8		[15] BOGOLYUB...	97	MIRA		32 $pp \to \pi^+\pi^- X$
761.1±2.9		DUBNICKA	89	RVUE		π form factor
777.4±2.0		[16] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
769.5±0.7		[11,12] LANG	79	RVUE	0	
770 ±9		[12] ESTABROOKS	74	RVUE	0	17 $\pi^- p \to \pi^+\pi^- n$
773.5±1.7	11200	[7] JACOBS	72	HBC	0	2.8 $\pi^- p$
775 ±3	2250	HYAMS	68	OSPK	0	11.2 $\pi^- p$



[1] From the Gounaris-Sakurai parametrization of the pion form factor. The second error is a model error taking into account different parametrizations of the pion form factor.

[2] From the Gounaris-Sakurai parametrization of the pion form factor.

[3] Using the data of BARKOV 85 and near-threshold behavior of the time-like pion form factor in the hidden local symmetry model.

[4] A fit of BARKOV 85 data assuming the direct $\omega\pi\pi$ coupling.

[5] Applying the S-matrix formalism to the BARKOV 85 data.

[6] Includes BARKOV 85 data. Model-dependent width definition.

[7] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[8] Phase shift analysis. Systematic errors added corresponding to spread of different fits.

[9] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.

[10] HEYN 81 includes all spacelike and timelike F_π values until 1978.

[11] From pole extrapolation.

[12] From phase shift analysis of GRAYER 74 data.

[13] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

[14] Systematic errors not evaluated.

[15] Systematic effects not studied.

[16] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.

$m_{\rho(770)^0} - m_{\rho(770)^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.1±0.9 OUR AVERAGE						
0.0±1.0		[17] BARATE	97M	ALEP		$\tau^- \to \pi^-\pi^0\nu_\tau$
−4 ±4	3000	[18] REYNOLDS	69	HBC	−0	2.26 $\pi^- p$
−5 ±5	3600	[18] FOSTER	68	HBC	±0	0.0 $\overline{p}p$
2.4±2.1	22950	[19] PISUT	68	RVUE		$\pi N \to \rho N$

[17] Using the compilation of e^+e^- data from BARKOV 85.

[18] From quoted masses of charged and neutral modes.

[19] Includes MALAMUD 69, ARMENISE 68, BATON 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65, CARMONY 64, GOLDHABER 64, ABOLINS 63.

$\rho(770)$ RANGE PARAMETER

The range parameter R enters an energy-dependent correction to the width, of the form $(1 + q_r^2\, R^2)\ /\ (1 + q^2\, R^2)$, where q is the momentum of one of the pions in the $\pi\pi$ rest system. At resonance, $q = q_r$.

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
$5.3^{+0.9}_{-0.7}$	CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized

$\rho(770)$ WIDTH

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
150.7±1.1 OUR AVERAGE	Includes data from the 4 datablocks that follow this one.

MIXED CHARGES, τ DECAYS and e^+e^-

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150.5±2.7 OUR AVERAGE					
150.5±1.6±6.3	[20] BARATE	97M	ALEP		$\tau^- \to \pi^-\pi^0\nu_\tau$
150.5±3.0	[21] BARKOV	85	OLYA	0	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
147.9±1.5	[22] BENAYOUN	98	RVUE		$e^+e^- \to \pi^+\pi^-, \mu^+\mu^-$
145.0±1.7	[23] O'CONNELL	97	RVUE		$e^+e^- \to \pi^+\pi^-$
142.5±3.5	[24] BERNICHA	94	RVUE		$e^+e^- \to \pi^+\pi^-$
138 ±1	[25] GESHKEN...	89	RVUE		$e^+e^- \to \pi^+\pi^-$

CHARGED ONLY, HADROPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150.2± 2.4 OUR FIT						
150.2± 2.4 OUR AVERAGE						
152.8± 4.3		ABELE	97	CBAR		$\overline{p}n \to \pi^-\pi^0\pi^0$
155 ±11	2935	[26] CAPRARO	87	SPEC	−	200 π^- Cu $\to \pi^-\pi^0$ Cu
154 ±20	967	[26] CAPRARO	87	SPEC	−	200 π^- Pb $\to \pi^-\pi^0$ Pb
150 ± 5		HUSTON	86	SPEC	+	202 π^+ A $\to \pi^+\pi^0$ A
146 ±12	6500	[27] BYERLY	73	OSPK	−	5 $\pi^- p$
148.2± 4.1	9650	[28] PISUT	68	RVUE	−	1.7–3.2 $\pi^- p$, $t<10$
146 ±13	900	EISNER	67	HBC	−	4.2 $\pi^- p$, $t<10$

NEUTRAL ONLY, PHOTOPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150.9± 3.0		BARTALUCCI	78	CNTR	0	$\gamma p \to e^+e^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
147 ±11		GLADDING	73	CNTR	0	2.9–4.7 γp
155 ±12	2430	BALLAM	72	HBC	0	4.7 γp
145 ±13	1930	BALLAM	72	HBC	0	2.8 γp
140 ± 5		ALVENSLEB...	70	CNTR	0	γA, $t<0.01$
146.1± 2.9	140k	BIGGS	70	CNTR	0	<4.1 γC $\to \pi^+\pi^-$ C
160 ±10		LANZEROTTI	68	CNTR	0	γp
130 ± 5	4000	ASBURY	67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150.9± 2.0 OUR FIT	Error includes scale factor of 1.3.					
150.9± 1.7 OUR AVERAGE	Error includes scale factor of 1.1.					
122 ±20		BERTIN	97C	OBLX		0.0 $\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
145.7± 5.3		WEIDENAUER	93	ASTE		$\overline{p}p \rightarrow \pi^+\pi^-\omega$
144.9± 3.7		DUBNICKA	89	RVUE		π form factor
148 ± 6		[29,30] BOHACIK	80	RVUE	0	
152 ± 9		[27] WICKLUND	78	ASPK	0	3,4,6 $\pi^{\pm}pN$
154 ± 2	76000	DEUTSCH...	76	HBC	0	16 π^+p
157 ± 8	6800	RATCLIFF	72	ASPK	0	15 π^-p, t <0.3
143 ± 8	1700	REYNOLDS	69	HBC	0	2.26 π^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •						
146 ± 3	4943	[31] ADAMS	97	E665		470 $\mu p \rightarrow \mu XB$
$160.0^{+4.1}_{-4.0}$		[32] CHABAUD	83	ASPK	0	17 π^-p polarized
155 ± 1		[33] HEYN	81	RVUE	0	π form factor
148.0± 1.3		[29,30] LANG	79	RVUE	0	
146 ±14	4100	ENGLER	74	DBC	0	6 $\pi^+n \rightarrow \pi^+\pi^-p$
143 ±13		[30] ESTABROOKS	74	RVUE	0	17 $\pi^-p \rightarrow \pi^+\pi^-n$
160 ±10	32000	[29] PROTOPOP...	73	HBC	0	7.1 π^+p, t <0.4
145 ±12	2250	[26] HYAMS	68	OSPK	0	11.2 π^-p
163 ±15	13300	[34] PISUT	68	RVUE	0	1.7–3.2 π^-p, t <10

[20] From the Gounaris-Sakurai parametrization of the pion form factor. The second error is a model error taking into account different parametrizations of the pion form factor.

[21] From the Gounaris-Sakurai parametrization of the pion form factor.

[22] Using the data of BARKOV 85 and near-threshold behavior of the time-like pion form factor in the hidden local symmetry model.

[23] A fit of BARKOV 85 data assuming the direct $\omega\pi\pi$ coupling.

[24] Applying the S-matrix formalism to the BARKOV 85 data.

[25] Includes BARKOV 85 data. Model-dependent width definition.

[26] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[27] Phase shift analysis. Systematic errors added corresponding to spread of different fits.

[28] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.

[29] From pole extrapolation.

[30] From phase shift analysis of GRAYER 74 data.

[31] Systematic errors not evaluated.

[32] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.

[33] HEYN 81 includes all spacelike and timelike F_{π} values until 1978.

[34] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

$\Gamma_{\rho(770)^0} - \Gamma_{\rho(770)^{\pm}}$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.1±1.9	[35] BARATE	97M	ALEP	$\tau^- \rightarrow \pi^-\pi^0\nu_{\tau}$

[35] Using the compilation of e^+e^- data from BARKOV 85.

$\rho(770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	~ 100 %	
	$\rho(770)^{\pm}$ decays		
Γ_2	$\pi^{\pm}\pi^0$	~ 100 %	
Γ_3	$\pi^{\pm}\gamma$	(4.5 ±0.5) × 10^{-4}	S=2.2
Γ_4	$\pi^{\pm}\eta$	< 6 × 10^{-3}	CL=84%
Γ_5	$\pi^{\pm}\pi^+\pi^-\pi^0$	< 2.0 × 10^{-3}	CL=84%
	$\rho(770)^0$ decays		
Γ_6	$\pi^+\pi^-$	~ 100 %	
Γ_7	$\pi^+\pi^-\gamma$	(9.9 ±1.6) × 10^{-3}	
Γ_8	$\pi^0\gamma$	(6.8 ±1.7) × 10^{-4}	
Γ_9	$\eta\gamma$	($2.4^{+0.8}_{-0.9}$) × 10^{-4}	S=1.6
Γ_{10}	$\mu^+\mu^-$	[a] (4.60±0.28) × 10^{-5}	
Γ_{11}	e^+e^-	[a] (4.49±0.22) × 10^{-5}	
Γ_{12}	$\pi^+\pi^-\pi^0$	< 1.2 × 10^{-4}	CL=90%
Γ_{13}	$\pi^+\pi^-\pi^+\pi^-$	< 2 × 10^{-4}	CL=90%
Γ_{14}	$\pi^+\pi^-\pi^0\pi^0$	< 4 × 10^{-5}	CL=90%

[a] The e^+e^- branching fraction is from $e^+e^- \rightarrow \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \rightarrow \mu^+\mu^-) = \Gamma(\rho^0 \rightarrow e^+e^-) \times 0.99785$.

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 10 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 10.7$ for 8 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc}
x_3 & -100 & \\
\Gamma & 15 & -15 \\
\hline
 & x_2 & x_3
\end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_2	$\pi^{\pm}\pi^0$	150.2 ±2.4	
Γ_3	$\pi^{\pm}\gamma$	0.068±0.007	2.3

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and a branching ratio uses 10 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 = 9.9$ for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

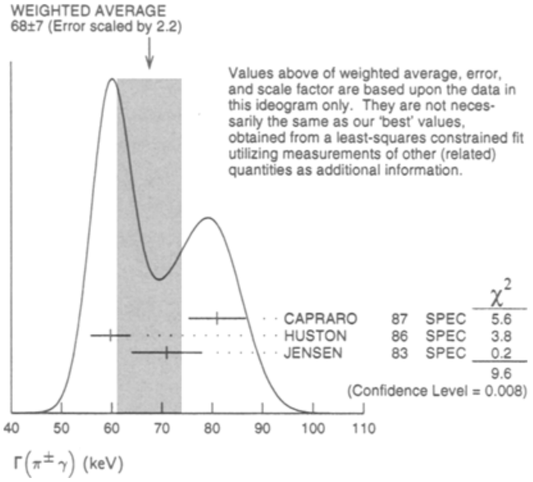
$$\begin{array}{c|ccc}
x_{10} & -79 & & \\
x_{11} & -61 & 0 & \\
\Gamma & 16 & 0 & -27 \\
\hline
 & x_6 & x_{10} & x_{11}
\end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_6	$\pi^+\pi^-$	150.8 ±2.0	1.3
Γ_{10}	$\mu^+\mu^-$	[a] 0.0069 ±0.0004	
Γ_{11}	e^+e^-	[a] 0.00677±0.00032	

$\rho(770)$ PARTIAL WIDTHS

$\Gamma(\pi^{\pm}\gamma)$ Γ_3

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
68 ±7 OUR FIT	Error includes scale factor of 2.3.				
68 ±7 OUR AVERAGE	Error includes scale factor of 2.2. See the ideogram below.				
81 ±4 ±4	CAPRARO	87	SPEC	−	200 $\pi^-A \rightarrow \pi^-\pi^0A$
59.8±4.0	HUSTON	86	SPEC	+	202 $\pi^+A \rightarrow \pi^+\pi^0A$
71 ±7	JENSEN	83	SPEC	−	156–260 $\pi^-A \rightarrow \pi^-\pi^0A$



$\Gamma(e^+e^-)$ Γ_{11}

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
6.77±0.32 OUR FIT			
6.77±0.10±0.30	BARKOV 85	OLYA	$e^+e^- \rightarrow \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
6.3 ±0.1	[36] BENAYOUN 98	RVUE	$e^+e^- \rightarrow \pi^+\pi^-$, $\mu^+\mu^-$

[36] Using the data of BARKOV 85 and near-threshold behavior of the time-like pion form factor in the hidden local symmetry model.

$\Gamma(\pi^0\gamma)$ Γ_8

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
121±31	DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^0\gamma$

$\Gamma(\eta\gamma)$ Γ_9

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
62±17	[37] DOLINSKY 89	ND	$e^+e^- \rightarrow \eta\gamma$

[37] Solution corresponding to constructive ω-ρ interference.

$\rho(770)$ BRANCHING RATIOS

$\Gamma(\pi^\pm\eta)/\Gamma(\pi\pi)$ Γ_4/Γ_1

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<60	84	FERBEL 66	HBC	±	$\pi^\pm p$ above 2.5

$\Gamma(\pi^\pm\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ Γ_5/Γ_1

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<20	84	FERBEL 66	HBC	±	$\pi^\pm p$ above 2.5
• • • We do not use the following data for averages, fits, limits, etc. • • •					
35±40		JAMES 66	HBC	+	2.1 π^+p

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_{10}/Γ_6

VALUE (units 10^{-5})	*DOCUMENT ID*	*TECN*	*COMMENT*
4.60±0.28 OUR FIT			
4.6 ±0.2 ±0.2	ANTIPOV 89	SIGM	$\pi^-\text{Cu} \rightarrow \mu^+\mu^-\pi^-\text{Cu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$8.2\ ^{+1.6}_{-3.6}$	[38] ROTHWELL 69	CNTR	Photoproduction
5.6 ±1.5	[39] WEHMANN 69	OSPK	12 π^- C, Fe
$9.7\ ^{+3.1}_{-3.3}$	[40] HYAMS 67	OSPK	11 π^- Li, H

[38] Possibly large ρ-ω interference leads us to increase the minus error.

[39] Result contains 11 ± 11% correction using SU(3) for central value. The error on the correction takes account of possible ρ-ω interference and the upper limit agrees with the upper limit of $\omega \rightarrow \mu^+\mu^-$ from this experiment.

[40] HYAMS 67's mass resolution is 20 MeV. The ω region was excluded.

$\Gamma(e^+e^-)/\Gamma(\pi\pi)$ Γ_{11}/Γ_1

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
0.41±0.05	BENAKSAS 72	OSPK	e^+e^-

$\Gamma(\eta\gamma)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
$2.4^{+0.8}_{-0.9}$ OUR AVERAGE Error includes scale factor of 1.6.				
$1.9^{+0.6}_{-0.8}$	[41] BENAYOUN 96	RVUE		0.54-1.04 $e^+e^- \rightarrow \eta\gamma$
3.6±0.9	[42] ANDREWS 77	CNTR	0	6.7-10 γCu
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.0±1.1	[42] DOLINSKY 89	ND		$e^+e^- \rightarrow \eta\gamma$

[41] Reanalysis of DRUZHININ 84, DOLINSKY 89, and DOLINSKY 91 taking into account a triangle anomaly contribution. Constructive ρ-ω interference solution.

[42] Solution corresponding to constructive ω-ρ interference.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<2	90	KURDADZE 88	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma(\pi\pi)$ Γ_{13}/Γ_1

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<15	90	ERBE 69	HBC	0	2.5–5.8 γp
<20		CHUNG 68	HBC	0	3.2,4.2 π^-p
<20	90	HUSON 68	HLBC	0	16.0 π^-p
<80		JAMES 66	HBC	0	2.1 π^+p

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.2	90	VASSERMAN 88B	ND	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ Γ_{12}/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~0.01		BRAMON 86	RVUE	0	$J/\psi \rightarrow \omega\pi^0$
<0.01	84	[43] ABRAMS 71	HBC	0	3.7 π^+p

[43] Model dependent, assumes I = 1, 2, or 3 for the 3π system.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.4	90	AULCHENKO 87C	ND	0	$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2	90	KURDADZE 86	OLYA	0	$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0099±0.0016		[44] DOLINSKY 91	ND	$e^+e^- \rightarrow \pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0111±0.0014		[45] VASSERMAN 88	ND	$e^+e^- \rightarrow \pi^+\pi^-\gamma$
<0.005	90	[46] VASSERMAN 88	ND	$e^+e^- \rightarrow \pi^+\pi^-\gamma$

[44] Bremsstrahlung from a decay pion and for photon energy above 50 MeV.

[45] Superseded by DOLINSKY 91.

[46] Structure radiation due to quark rearrangement in the decay.

$\Gamma(\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
6.8±1.7	[47] BENAYOUN 96	RVUE	0.54-1.04 $e^+e^- \rightarrow \pi^0\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
7.9±2.0	DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^0\gamma$

[47] Reanalysis of DRUZHININ 84, DOLINSKY 89, and DOLINSKY 91 taking into account a triangle anomaly contribution.

$\rho(770)$ REFERENCES

BENAYOUN	98	EPJ C2 269	M. Benayoun+	(IPNP, NOVO, ADLD, KNTY)
ABELE	97	PL B391 191	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
ADAMS	97	ZPHY C74 237	M.R. Adams+	(E665 Collab.)
BARATE	97M	ZPHY C76 15	R. Barate+	(ALEPH Collab.)
BERTIN	97C	PL B408 476	A. Bertin, Bruschi+	(OBELIX Collab.)
BOGOLYUB...	97	PAN 60 46 Translated from YAF 60 53.	Bogolyubsky, Bravina, Kiryunin+	(MOSU, SERP)
O'CONNELL	97	NP A623 559	H.B. O'Connell, Thomas, Williams+	(ADLD)
BENAYOUN	96	ZPHY C72 221	M. Benayoun+	(IPNP, NOVO)
BERNICHA	94	PR D50 4454	+Lopez Castro, Pestieau	(LOUV, CINV)
WEIDENAUER	93	ZPHY C59 387	+Duch+	(ASTERIX Collab.)
AGUILAR-...	91	ZPHY C50 405	Aguilar-Benitez, Allison, Batalor+	(LEBC-EHS Collab.)
DOLINSKY	91	PRPL 202 99	+Druzhinin, Dubrovin+	(NOVO)
ANTIPOV	89	ZPHY C42 185	+Batarin+	(SERP, JINR, BGNA, MILA, TBIL)
DOLINSKY	89	ZPHY C42 511	+Druzhinin, Dubrovin, Golubev+	(NOVO)
DUBNICKA	89	JPG 15 1349	+Martinovic+	(JINR, SLOV)
GESHKEN...	89	ZPHY 45 351	Geshkenbein	(ITEP)
KURDADZE	88	JETPL 47 512 Translated from ZETFP 47 432.	+Leitchouk, Pakhtusova, Sidorov+	(NOVO)
VASSERMAN	88	SJNP 47 1035 Translated from YAF 47 1635.	+Golubev, Dolinsky+	(NOVO)
VASSERMAN	88B	SJNP 48 480 Translated from YAF 48 753.	+Golubev, Dolinsky+	(NOVO)
AULCHENKO	87C	IYF 87-90 Preprint	+Dolinsky, Druzhinin+	(NOVO)
CAPRARO	87	NP B288 659	+Levy+	(CLER, FRAS, MILA, PISA, LCGT, TRST+)
BRAMON	86	PL B173 97	+Casulleras	(BARC)
HUSTON	86	PR 33 3199	+Berg, Collick, Jonckheere+	(ROCH, FNAL, MINN)
KURDADZE	86	JETPL 43 643 Translated from ZETFP 43 497.	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
DRUZHININ	84	PL 144B 136	+Golubev, Ivanchenko, Peryshkin+	(NOVO)
CHABAUD	83	NP B223 1	+Gorlich, Cerrada+	(CERN, CRAC, MPIM)
JENSEN	83	PR D27 26	+Berg, Biel, Collick+	(ROCH, FNAL, MINN)
HEYN	81	ZPHY C7 169	+Lang	(GRAZ)
BOHACIK	80	PR D21 1342	+Kuhnelt	(SLOV, WIEN)
LANG	79	PR D19 956	+Mas-Parareda	(GRAZ)
BARTALUCCI	78	NC 44A 587	+Basini, Bertolucci+	(DESY, FRAS)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
DEUTSCH...	76	NP B103 426	Deutschmann+	(AACH3, BERL, BONN, CERN+)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
ESTABROOKS	74	NP B79 301	+Martin	(DURH)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
BYERLY	73	PR D7 637	+Anthony, Coffin, Meanley, Meyer, Rice+	(MICH)
GLADDING	73	PR D8 3721	+Russell, Tannenbaum, Weiss, Thomson	(HARV)
PROTOPOP...	73	PR D7 1279	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)
BALLAM	72	PR D5 545	+Chadwick, Bingham, Milburn+	(SLAC, LBL, TUFTS)
BENAKSAS	72	PL 39B 289	+Cosme, Jean-Marie, Jullian, Laplanche+	(ORSAY)
JACOBS	72	PR D6 1291		(SACL)
RATCLIFF	72	PL 38B 345	+Bulos, Carnegie, Kluge, Leith, Lynch+	(SLAC)
ABRAMS	71	PR D4 653	+Barnham, Butler, Coyne, Goldhaber, Hall+	(LBL)
ALVENSLEB...	70	PRL 24 786	Alvensleben, Becker, Bertram, Chen, Cohen	(DESY)
BIGGS	70	PRL 24 1197	+Braben, Clifft, Gabathuler, Kitching+	(DARE)
ERBE	69	PR 188 2060	+Hilpert+	(German Bubble Chamber Collab.)
MALAMUD	69	Argonne Conf. 93	+Schlein	(UCLA)
REYNOLDS	69	PR 184 1424	+Albright, Bradley, Brucker, Harms+	(FSU)
ROTHWELL	69	PRL 23 1521	+Chase, Earles, Gettner, Glass, Weinstein+	(NEAS)
WEHMANN	69	PR 178 2095	+	(HARV, CASE, SLAC, CORN, MCGI)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSAY)
BATON	68	PR 176 1574	+Laurens	(SACL)

CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
FOSTER 68 NP B6 107 +Gavillet, Labrosse, Montanet+ (CERN, CDEF)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSAY, MILA, UCLA)
HYAMS 68 NP B7 1 +Koch, Potter, Wilson, VonLindern+ (CERN, MPIM)
LANZEROTTI 68 PR 166 1365 +Blumenthal, Ehn, Faissler+ (HARV)
PISUT 68 NP B6 325 +Roos (CERN)
ASBURY 67B PRL 19 865 +Becker, Bertram, Joos, Jordan+ (DESY, COLU)
BACON 67 PR 157 1263 +Fickinger, Hill, Hopkins, Robinson+ (BNL)
EISNER 67 PR 164 1699 +Johnson, Klein, Peters, Sahni, Yen+ (PURD)
HUWE 67 PL 24B 252 +Marquit, Oppenheimer, Schultz, Wilson (COLU)
HYAMS 67 PL 24B 634 +Koch, Pellett, Potter, VonLindern+ (CERN, MPIM)
MILLER 67B PR 153 1423 +Gutay, Johnson, Loeffler+ (PURD)
ALFF-... 66 PR 145 1072 Alff-Steinberger, Berley+ (COLU, RUTG)
FERBEL 66 PL 21 111 (ROCH)
HAGOPIAN 66 PR 145 1128 +Selove, Alitti, Baton+ (PENN, SACL)
HAGOPIAN 66B PR 152 1183 +Pan (PENN, LRL)
JACOBS 66B UCRL 16877 (LRL)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
WEST 66 PR 149 1089 +Boyd, Erwin, Walker (WISC)
BLIEDEN 65 PL 19 444 +Freytag, Geibel+ (CERN Missing Mass Spect. Collab.)
CARMONY 64 PRL 12 254 +Lander, Rindfleisch, Xuong, Yager (UCB)
GOLDHABER 64 PRL 12 336 +Brown, Kadyk, Shen+ (LRL, UCB)
ABOLINS 63 PRL 11 381 +Lander, Mehlhop, Nguyen, Yager (UCSD)

OTHER RELATED PAPERS

ABELE 97B PL B402 195 A. Abele, Adomeit, Amsler+ (Crystal Barrel Collab.)
ABELE 97F PL B411 354 A. Abele+ (Crystal Barrel Collab.)
BARATE 97M ZPHY C76 15 R. Barate+ (ALEPH Collab.)
BENAYOUN 93 ZPHY 58 31 +Feindt, Girone+ (CDEF, CERN, BARI)
LAFFERTY 93 ZPHY C60 659 (MCHS)
KAMAL 92 PL B284 421 +Xu (ALBE)
KUHN 90 ZPHY C48 445 J.H. Kuhn, Santamaria+ (MPIM)
ERKAL 85 ZPHY C29 485 +Olsson (WISC)
RYBICKI 85 ZPHY C28 65 +Sakrejda (CRAC)
KURDADZE 83 JETPL 37 733 +Lelchuk, Pakhtusova+ (NOVO)
Translated from ZETFP 37 613.
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
KENNEY 62 PR 126 736 +Shephard, Gall (KNTY)
SAMIOS 62 PRL 9 139 +Bachman, Lea+ (BNL, CUNY, COLU, KNTY)
XUONG 62 PR 128 1849 +Lynch (LRL)
ANDERSON 61 PRL 6 365 +Bang, Burke, Carmony, Schmitz (LRL)
ERWIN 61 PRL 6 628 +March, Walker, West (WISC)

$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

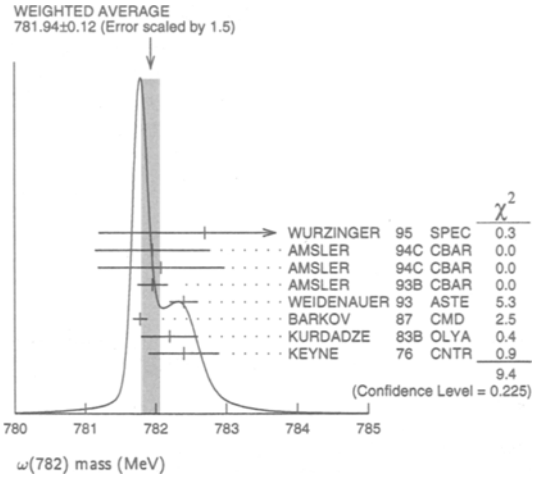
$\omega(782)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
781.94±0.12 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
782.7 ±0.1 ±1.5	19500	WURZINGER	95	SPEC	1.33 $pd \to {}^3\mathrm{He}\omega$
781.96±0.17±0.80	11k	AMSLER	94C	CBAR	0.0 $\overline{p}p \to \omega\pi^0\pi^0$
782.08±0.36±0.82	3463	AMSLER	94C	CBAR	0.0 $\overline{p}p \to \omega\eta\pi^0$
781.96±0.13±0.17	15k	AMSLER	93B	CBAR	0.0 $\overline{p}p \to \omega\pi^0\pi^0$
782.4 ±0.2	270k	WEIDENAUER	93	ASTE	$\overline{p}p \to 2\pi^+2\pi^-\pi^0$
781.78±0.10		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
782.2 ±0.4	1488	KURDADZE	83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
782.4 ±0.5	7000	[1] KEYNE	76	CNTR	$\pi^-p \to \omega n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
783.3 ±0.4		CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
782.5 ±0.8	33260	ROOS	80	RVUE	0.0–3.6 $\overline{p}p$
782.6 ±0.8	3000	BENKHEIRI	79	OMEG	9–12 $\pi^\pm p$
781.8 ±0.6	1430	COOPER	78B	HBC	0.7–0.8 $\overline{p}p \to 5\pi$
782.7 ±0.9	535	VANAPEL...	78	HBC	7.2 $\overline{p}p \to \overline{p}p\omega$
783.5 ±0.8	2100	GESSAROLI	77	HBC	11 $\pi^-p \to \omega n$
782.5 ±0.8	418	AGUILAR-...	72B	HBC	3.9,4.6 K^-p
783.4 ±1.0	248	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K^+K^-\omega$
781.0 ±0.6	510	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K_1K_1\omega$
783.7 ±1.0	3583	[2] COYNE	71	HBC	3.7 $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$
784.1 ±1.2	750	ABRAMOVI...	70	HBC	3.9 π^-p
783.2 ±1.6		[3] BIGGS	70B	CNTR	<4.1 $\gamma C \to \pi^+\pi^-C$
782.4 ±0.5	2400	BIZZARRI	69	HBC	0.0 $\overline{p}p$

[1] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.

[2] From best-resolution sample of COYNE 71.

[3] From ω-ρ interference in the $\pi^+\pi^-$ mass spectrum assuming ω width 12.6 MeV.



$\omega(782)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
8.41±0.09 OUR AVERAGE					
8.2 ±0.3	19500	WURZINGER	95	SPEC	1.33 $pd \to {}^3\mathrm{He}\omega$
8.4 ±0.1		[4] AULCHENKO	87	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
8.30±0.40		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
9.8 ±0.9	1488	KURDADZE	83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
9.0 ±0.8		CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
9.1 ±0.8		BENAKSAS	72B	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12 ±2	1430	COOPER	78B	HBC	0.7–0.8 $\overline{p}p \to 5\pi$
9.4 ±2.5	2100	GESSAROLI	77	HBC	11 $\pi^-p \to \omega n$
10.22±0.43	20000	[5] KEYNE	76	CNTR	$\pi^-p \to \omega n$
13.3 ±2	418	AGUILAR-...	72B	HBC	3.9,4.6 K^-p
10.5 ±1.5		BORENSTEIN	72	HBC	2.18 K^-p
7.70±0.9 ±1.15	940	BROWN	72	MMS	2.5 $\pi^-p \to n\mathrm{MM}$
10.3 ±1.4	510	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K_1K_1\omega$
12.8 ±3.0	248	BIZZARRI	71	HBC	0.0 $p\overline{p} \to K^+K^-\omega$
9.5 ±1.0	3583	COYNE	71	HBC	3.7 $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$

[4] Relativistic Breit-Wigner includes radiative corrections.

[5] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.

$\omega(782)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$		(88.8 ± 0.7) %	
Γ_2	$\pi^0\gamma$		(8.5 ± 0.5) %	
Γ_3	$\pi^+\pi^-$		(2.21 ± 0.30) %	
Γ_4	neutrals (excluding $\pi^0\gamma$)		$(5.3\,^{+8.7}_{-3.5}) \times 10^{-3}$	
Γ_5	$\eta\gamma$		$(6.5 \pm 1.0) \times 10^{-4}$	
Γ_6	$\pi^0e^+e^-$		$(5.9 \pm 1.9) \times 10^{-4}$	
Γ_7	$\pi^0\mu^+\mu^-$		$(9.6 \pm 2.3) \times 10^{-5}$	
Γ_8	e^+e^-		$(7.07 \pm 0.19) \times 10^{-5}$	S=1.1
Γ_9	$\pi^+\pi^-\pi^0\pi^0$		< 2 %	CL=90%
Γ_{10}	$\pi^+\pi^-\gamma$		$< 3.6 \times 10^{-3}$	CL=95%
Γ_{11}	$\pi^+\pi^-\pi^+\pi^-$		$< 1 \times 10^{-3}$	CL=90%
Γ_{12}	$\pi^0\pi^0\gamma$		$(7.2 \pm 2.5) \times 10^{-5}$	
Γ_{13}	$\mu^+\mu^-$		$< 1.8 \times 10^{-4}$	CL=90%
Γ_{14}	3γ		$< 1.9 \times 10^{-4}$	CL=95%
Charge conjugation (C) violating modes				
Γ_{15}	$\eta\pi^0$	C	$< 1 \times 10^{-3}$	CL=90%
Γ_{16}	$3\pi^0$	C	$< 3 \times 10^{-4}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to 6 branching ratios uses 20 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 = 10.3$ for 17 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc} x_2 & 13 & & \\ x_3 & -39 & -5 & \\ x_4 & -74 & -68 & -1 \\ \hline & x_1 & x_2 & x_3 \end{array}$$

$\omega(782)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_8

VALUE (keV)	DOCUMENT ID
0.60±0.02 OUR EVALUATION	

$\omega(782)$ BRANCHING RATIOS

$\Gamma(\text{neutrals})/\Gamma(\pi^+\pi^-\pi^0)$ $(\Gamma_2+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.102±0.008 OUR FIT				
$0.103^{+0.011}_{-0.010}$ OUR AVERAGE				
0.15 ±0.04	46	AGUILAR-... 72B	HBC	3.9,4.6 $K^- p$
0.10 ±0.03	19	BARASH 67B	HBC	0.0 $\overline{p}p$
0.134±0.026	850	DIGIUGNO 66B	CNTR	1.4 $\pi^- p$
0.097±0.016	348	FLATTE 66	HBC	1.4 – 1.7 $K^- p \rightarrow \Lambda$MM
$0.06 \ ^{+0.05}_{-0.02}$		JAMES 66	HBC	2.1 $\pi^+ p$
0.08 ±0.03	35	KRAEMER 64	DBC	1.2 $\pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11 ±0.02	20	BUSCHBECK 63	HBC	1.5 $K^- p$

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_3/Γ_1

See also $\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0249±0.0035 OUR FIT			
0.026 ±0.005 OUR AVERAGE			
$0.021 \ ^{+0.028}_{-0.009}$	[6] RATCLIFF 72	ASPK	15 $\pi^- p \rightarrow n 2\pi$
0.028 ±0.006	BEHREND 71	ASPK	Photoproduction
$0.022 \ ^{+0.009}_{-0.01}$	[7] ROOS 70	RVUE	

[6] Significant interference effect observed. NB of $\omega \rightarrow 3\pi$ comes from an extrapolation.

[7] ROOS 70 combines ABRAMOVICH 70 and BIZZARRI 70.

$\Gamma(\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.096±0.006 OUR FIT			
0.096±0.006 OUR AVERAGE			
0.099±0.007	DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^0\gamma$
0.084±0.013	KEYNE 76	CNTR	$\pi^- p \rightarrow \omega n$
0.109±0.025	BENAKSAS 72C	OSPK	e^+e^-
0.081±0.020	BALDIN 71	HLBC	2.9 $\pi^+ p$
0.13 ±0.04	JACQUET 69B	HLBC	

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{10}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.066	90	KALBFLEISCH 75	HBC	2.18 $K^- p \rightarrow \Lambda\pi^+\pi^-\gamma$
<0.05	90	FLATTE 66	HBC	1.2 – 1.7 $K^- p \rightarrow \Lambda\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0036	95	WEIDENAUER 90	ASTE	$p\overline{p} \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.004	95	BITYUKOV 88B	SPEC	32 $\pi^- p \rightarrow \pi^+\pi^-\gamma X$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1 \times 10^{-3}$	90	KURDADZE 88	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID	TECN	COMMENT
<2	90	KURDADZE 86	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{13}/Γ_1

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.2	90	WILSON 69	OSPK	12 π^- C $\rightarrow$ Fe
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	74	FLATTE 66	HBC	1.2 – 1.7 $K^- p \rightarrow \Lambda\mu^+\mu^-$
<1.2		BARBARO-... 65	HBC	2.7 $K^- p$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^0\gamma)$ Γ_{12}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.00085±0.00029		40 ± 14	ALDE 94B	GAM2	$38\pi^- p \rightarrow \pi^0\pi^0\gamma n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.005	90		DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^0\pi^0\gamma$
< 0.18	95		KEYNE 76	CNTR	$\pi^- p \rightarrow \omega n$
< 0.15	90		BENAKSAS 72C	OSPK	e^+e^-
< 0.14			BALDIN 71	HLBC	2.9 $\pi^+ p$
< 0.1	90		BARMIN 64	HLBC	1.3–2.8 $\pi^- p$

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ Γ_{15}/Γ

Violates *C* conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.001	90	ALDE 94B	GAM2	$38\pi^- p \rightarrow \eta\pi^0 n$

$[\Gamma(\eta\gamma)+\Gamma(\eta\pi^0)]/\Gamma(\pi^+\pi^-\pi^0)$ $(\Gamma_5+\Gamma_{15})/\Gamma_1$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.016	90	[8] FLATTE 66	HBC	1.2 – 1.7 $K^- p \rightarrow \Lambda\pi^+\pi^-$ MM
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.045	95	JACQUET 69B	HLBC	

[8] Restated by us using B($\eta \rightarrow$ charged modes) = 29.2%.

$\Gamma(\text{neutrals})/\Gamma(\text{charged particles})$ $(\Gamma_2+\Gamma_4)/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.099±0.008 OUR FIT			
0.124±0.021	FELDMAN 67C	OSPK	1.2 $\pi^- p$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00045	90	DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^0\pi^0\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	95	JACQUET 69B	HLBC	

$\Gamma(\eta\gamma)/\Gamma(\pi^0\gamma)$ Γ_5/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0098±0.0024	[9] ALDE 93	GAM2	$38\pi^- p \rightarrow \omega n$
0.0082±0.0033	[10] DOLINSKY 89	ND	$e^+e^- \rightarrow \eta\gamma$
0.010 ±0.045	APEL 72B	OSPK	4–8 $\pi^- p \rightarrow n 3\gamma$

[9] Model independent determination.

[10] Solution corresponding to constructive ω-ρ interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
0.96±0.23	DZHELYADIN 81B	CNTR	25–33 $\pi^- p \rightarrow \omega n$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
5.9±1.9	43	DOLINSKY 88	ND	$e^+e^- \rightarrow \pi^0 e^+e^-$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
0.707±0.019 OUR AVERAGE		Error includes scale factor of 1.1.		
0.714±0.036		DOLINSKY 89	ND	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
0.72 ±0.03		BARKOV 87	CMD	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
0.64 ±0.04	1488	KURDADZE 83B	OLYA	$e^+e^- \rightarrow \pi^+\pi^-\pi^0$
0.675±0.069		CORDIER 80	WIRE	$e^+e^- \rightarrow 3\pi$
0.83 ±0.10		BENAKSAS 72B	OSPK	$e^+e^- \rightarrow 3\pi$
0.77 ±0.06		[11] AUGUSTIN 69D	OSPK	$e^+e^- \rightarrow 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65 ±0.13	33	[12] ASTVACAT... 68	OSPK	Assume SU(3)+mixing

[11] Rescaled by us to correspond to ω width 8.4 MeV.

[12] Not resolved from ρ decay. Error statistical only.

$\Gamma(\text{neutrals})/\Gamma_{\text{total}}$ $(\Gamma_2+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.090±0.006 OUR FIT				
0.081±0.011 OUR AVERAGE				
0.075±0.025		BIZZARRI 71	HBC	0.0 $p\overline{p}$
0.079±0.019		DEINET 69B	OSPK	1.5 $\pi^- p$
0.084±0.015		BOLLINI 68C	CNTR	2.1 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.073±0.018	42	BASILE 72B	CNTR	1.67 $\pi^- p$

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_3/Γ

See also $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0221±0.0030 OUR FIT				
0.021 ±0.004 OUR AVERAGE				
0.023 ±0.005	BARKOV	85	OLYA	e^+e^-
$0.016^{+0.009}_{-0.007}$	QUENZER	78	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.023 ±0.004	[13] BENAYOUN	98	RVUE	$e^+e^- \to \pi^+\pi^-, \mu^+\mu^-$
0.010 ±0.001	[14] WICKLUND	78	ASPK	3,4,6 $\pi^\pm N$
0.0122±0.0030	ALVENSLEB...	71C	CNTR	Photoproduction
$0.013^{+0.012}_{-0.009}$	MOFFEIT	71	HBC	2.8,4.7 γp
$0.0080^{+0.0028}_{-0.002}$	[15] BIGGS	70B	CNTR	$4.2 \gamma C \to \pi^+\pi^- C$

[13] Not independent of BARKOV 85.

[14] From a model-dependent analysis assuming complete coherence.

[15] Re-evaluated under $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ by BEHREND 71 using more accurate $\omega \to \rho$ photoproduction cross-section ratio.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\text{neutrals})$ $\Gamma_{12}/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.22±0.07		[16] DAKIN	72	OSPK	1.4 $\pi^- p \to n MM$
<0.19	90	DEINET	69B	OSPK	

[16] See $\Gamma(\pi^0\gamma)/\Gamma(\text{neutrals})$.

$\Gamma(\pi^0\gamma)/\Gamma(\text{neutrals})$ $\Gamma_2/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.78±0.07		[17] DAKIN	72	OSPK	1.4 $\pi^- p \to n MM$
>0.81	90	DEINET	69B	OSPK	

[17] Error statistical only. Authors obtain good fit also assuming $\pi^0\gamma$ as the only neutral decay.

$\Gamma(\eta\gamma)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
6.5 ±1.0 OUR AVERAGE					
6.6 ±1.7		ABELE	97E	CBAR	0.0 $\bar{p}p \to 5\gamma$
8.3 ±2.1		ALDE	93	GAM2	$38\pi^- p \to \omega n$
7.3 ±2.9		[18] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$
$3.0^{+2.5}_{-1.8}$		[18] ANDREWS	77	CNTR	6.7–10 γCu
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$6.56^{+2.41}_{-2.55}$	3525	[18,19] BENAYOUN	96	RVUE	$e^+e^- \to \eta\gamma$

[18] Solution corresponding to constructive ω-ρ interference.

[19] Reanalysis of DRUZHININ 84, DOLINSKY 89, DOLINSKY 91 taking into account the triangle anomaly contributions.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma(\mu^+\mu^-)$ Γ_7/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.2±0.6	30	[20] DZHELYADIN	79	CNTR	25–33 $\pi^- p$

[20] Superseded by DZHELYADIN 81B result above.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.8942±0.0062	DOLINSKY	89	ND	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(3\pi^0)/\Gamma_{\rm total}$ Γ_{16}/Γ

Violates *C* conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0003	90	PROKOSHKIN	95	GAM2	$38\ \pi^- p \to 3\pi^0 n$

$\Gamma(3\gamma)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.9	95	[21] ABELE	97E	CBAR	0.0 $\bar{p}p \to 5\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2	90	[21] PROKOSHKIN	95	GAM2	$38\ \pi^- p \to 3\gamma n$

[21] From direct 3γ decay search.

$\Gamma(\pi^0\gamma)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.39±0.24	9975	[22] BENAYOUN	96	RVUE	$e^+e^- \to \pi^0\gamma$

[22] Reanalysis of DRUZHININ 84, DOLINSKY 89, DOLINSKY 91 taking into account the triangle anomaly contributions.

$\omega(782)$ REFERENCES

BENAYOUN	98	EPJ C2 269	M. Benayoun+	(IPNP, NOVO, ADLD, KNTY)
ABELE	97E	PL B411 361	A. Abele+	(Crystal Barrel Collab.)
BENAYOUN	96	ZPHY C72 221	M. Benayoun+	(IPNP, NOVO)
PROKOSHKIN	95	SPD 342 273	+Samoilenko	(SERP)
		Translated from DANS 342 610.		
WURZINGER	95	PR C51 443	+Siebert+	(BONN, ORSAY, SACL, LOUC, CRAC)
ALDE	94B	PL B340 122	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP, MONT)
AMSLER	94C	PL B327 425	+Armstrong, Ravndal+	(Crystal Barrel Collab.)
ALDE	93	PAN 56 1229	+Binon+	(SERP, LAPP, LANL, BELG, BRUX, CERN)
		Translated from YAF 56 137.		
Also	94	ZPHY C61 35	Alde, Binon+	(SERP, LAPP, LANL, BELG, BRUX, CERN)
AMSLER	93B	PL B311 362	+Armstrong, v.Dombrowski+	(Crystal Barrel Collab.)
WEIDENAUER	93	ZPHY C59 387	+Duch+	(ASTERIX Collab.)
DOLINSKY	91	PRPL 202 99	+Druzhinin, Dubrovin+	(NOVO)
WEIDENAUER	90	ZPHY C47 353	+Duch, Heel, Kalinowsky+	(ASTERIX Collab.)
DOLINSKY	89	ZPHY C42 511	+Druzhinin, Dubrovin, Golubev+	(NOVO)
BITYUKOV	88B	SJNP 47 800	+Borisov, Viktorov, Golovkin+	(SERP)
		Translated from YAF 47 1258.		
DOLINSKY	88	SJNP 48 277	+Druzhinin, Dubrovin, Golubev+	(NOVO)
		Translated from YAF 48 442.		
KURDADZE	88	JETPL 47 512	+Leitchouk, Pakhtusova, Sidorov+	(NOVO)
		Translated from ZETFP 47 432.		
AULCHENKO	87	PL B186 432	+Dolinsky, Druzhinin, Dubrovin+	(NOVO)
BARKOV	87	JETPL 46 164	+Vasserman, Vorobev, Ivanov	(NOVO)
		Translated from ZETFP 46 132.		
KURDADZE	86	JETPL 43 643	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
		Translated from ZETFP 43 497.		
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
DRUZHININ	84	PL 144B 136	+Golubev, Ivanchenko, Peryshkin+	(NOVO)
KURDADZE	83B	JETPL 36 274	+Pakhtusova, Sidorov+	(NOVO)
		Translated from ZETFP 36 221.		
DZHELYADIN	81B	PL 102B 296	+Golovkin, Konstantinov+	(SERP)
CORDIER	80	NP B172 13	+Delcourt, Eschstruth, Fulda+	(LALO)
ROOS	80	LNC 27 321	+Pellinen	(HELS)
BENKHEIRI	79	NP B150 268	+Eisenstein+	(EPOL, CERN, CDEF, LALO)
DZHELYADIN	79	PL 84B 143	+Golovkin, Gritsuk+	(SERP)
COOPER	78B	NP B146 1	+Ganguli+	(TATA, CERN, CDEF, MADR)
QUENZER	78	PL 76B 512	+Ribes, Rumpf, Bertrand, Bizot, Chase+	(LALO)
VANAPEL...	78	NP B133 245	VanApeldoorn, Grundeman, Harting+	(ZEEM)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
KEYNE	76	PR D14 28	+Binnie, Carr, Debenham, Garbutt+	(LOIC, SHMP)
Also	73B	PR D8 2789	Binnie, Carr, Debenham, Duane+	(LOIC, SHMP)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
APEL	72B	PL 41B 234	+Auslander, Muller, Bertolucci+	(KARLK, KARLE, PISA)
BASILE	72B	Phil. Conf. 153	+Bollini, Broglin, Dalpiaz, Frabetti+	(CERN)
BENAKSAS	72B	PL 42B 507	+Cosme, Jean-Marie, Jullian	(ORSAY)
BENAKSAS	72C	PL 42B 511	+Cosme, Jean-Marie, Jullian, Laplanche+	(ORSAY)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH)
BROWN	72	PL 42B 117	+Downing, Holloway, Huld, Bernstein+	(ILL, ILLC)
DAKIN	72	PR D6 2321	+Hauser, Kreisler, Mischke	(PRIN)
RATCLIFF	72	PL 38B 345	+Bulos, Carnegie, Kluge, Leith, Lynch+	(SLAC)
ALVENSLEB...	71C	PRL 27 888	Alvensleben, Becker, Busza, Chen, Cohen+	(DESY)
BALDIN	71	SJNP 13 758	+Yergakov, Trebukhovsky, Shishov	(ITEP)
		Translated from YAF 13 1318.		
BEHREND	71	PRL 27 61	+Lee, Nordberg, Wehmann+	(ROCH, CORN, FNAL)
BIZZARRI	71	NP B27 140	+Montanet, Nilsson, D'Andlau+	(CERN, CDEF)
COYNE	71	NP B32 333	+Butler, Fang-Landau, MacNaughton	(LRL)
MOFFEIT	71	NP B29 349	+Bingham, Fretter+	(LRL, UCB, SLAC, TUFTS)
ABRAMOVI...	70	NP B20 209	Abramovich, Blumenfeld, Bruyant+	(CERN)
BIGGS	70B	PRL 24 1201	+Clifft, Gabathuler, Kitching, Rand	(DARE)
BIZZARRI	70	PRL 25 1385	+Ciapetti, Dore, Gaspero, Guidoni+	(ROMA, SYRA)
ROOS	70	DNPL/R7 173		(CERN)
Proc. Daresbury Study Weekend No. 1.				
AUGUSTIN	69D	PL 28B 513	+Benaksas, Buon, Gracco, Haissinski+	(ORSAY)
BIZZARRI	69	NP B14 169	+Foster, Gavillet, Montanet+	(CERN, CDEF)
DEINET	69B	PL 30B 426	+Menzione, Muller, Buniatov+	(KARL, CERN)
JACQUET	69B	NC 63A 743	+Nguyen-Khac, Haatuft, Halsteinslid	(EPOL, BERG)
WILSON	69	Private Comm.		(HARV)
Also	69	PR 178 2095	Wehmann+	(HARV, CASE, SLAC, CORN, MCGI)
ASTVACAT...	68	PL 27B 45	Astvacaturov, Azimov, Baldin+	(JINR, MOSU)
BOLLINI	68C	NC 56A 531	+Buhler, Dalpiaz, Massam+	(CERN, BGNA, STRB)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
FELDMAN	67C	PR 159 1219	+Frati, Gleeson, Halpern, Nussbaum+	(PENN)
DIGIUGNO	66B	NC 44A 1272	+Peruzzi, Troise+	(NAPL, FRAS, TRST)
FLATTE	66	PR 145 1050	+Huwe, Murray, Button-Shafer, Solmitz+	(LRL)
JAMES	66	PR 142 896	+Kraybill	(YALE, BNL)
BARBARO-...	65	PRL 14 279	Barbaro-Galtieri, Tripp	(LRL)
BARMIN	64	JETP 18 1289	+Dolgolenko, Krestnikov+	(ITEP)
		Translated from ZETF 45 1879.		
KRAEMER	64	PR 136B 496	+Madansky, Fields+	(JHU, NWES, WOOD)
BUSCHBECK	63	Siena Conf. 1 166	+Czapp+	(VIEN, CERN, ANIK)

OTHER RELATED PAPERS

ABELE	97F	PL B411 354	A. Abele+	(Crystal Barrel Collab.)
DOLINSKY	86	PL B174 453	+Druzhinin, Dubrovin, Eidelman+	(NOVO)
KURDADZE	83	JETPL 37 733	+Lelchuk, Pakhtusova+	(NOVO)
		Translated from ZETFP 37 613.		
ALFF-...	62B	PRL 9 325	Alff-Steinberger, Berley, Colley+	(COLU, RUTG)
STEVENSON	62	PR 125 687	+Alvarez, Maglich, Rosenfeld	(LRL)
MAGLICH	61	PRL 7 178	+Alvarez, Rosenfeld, Stevenson	(LRL)
PEVSNER	61	PRL 7 421	+Kraemer, Nussbaum, Richardson+	(JHU)
XUONG	61	PRL 7 327	+Lynch	(LRL)

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

$\eta'(958)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
957.78±0.14 OUR AVERAGE					
957.9 ±0.2 ±0.6	4800	WURZINGER	96	SPEC	1.68 $pd \to {}^3\text{He}\eta'$
959 ±1	630	BELADIDZE	92C	VES	36 $\pi^- \text{Be} \to \pi^-\eta'\eta\text{Be}$
958 ±1	340	ARMSTRONG	91B	OMEG	300 $pp \to pp\eta\pi^+\pi^-$
958.2 ±0.4	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
957.8 ±0.2	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
956.3 ±1.0	143	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
957.46±0.33		DUANE	74	MMS	$\pi^- p \to n\text{MM}$
958.2 ±0.5	1414	DANBURG	73	HBC	2.2 $K^- p \to \Lambda X^0$
958 ±1	400	JACOBS	73	HBC	2.9 $K^- p \to \Lambda X^0$
956.1 ±1.1	3415	BASILE	71	CNTR	1.6 $\pi^- p \to nX^0$
957.4 ±1.4	535	BASILE	71	CNTR	1.6 $\pi^- p \to nX^0$
957 ±1		RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\eta'(958)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.203±0.016 OUR FIT Error includes scale factor of 1.3.						
0.30 ±0.09 OUR AVERAGE						
0.40 ±0.22	4800	WURZINGER	96	SPEC		1.68 $pd \to {}^3\text{He}\eta'$
0.28 ±0.10	1000	BINNIE	79	MMS	0	$\pi^- p \to n\text{MM}$

$\eta'(958)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\eta$		(43.8 ±1.5) %	S=1.1
Γ_2	$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)		(30.2 ±1.3) %	S=1.1
Γ_3	$\pi^0\pi^0\eta$		(20.7 ±1.3) %	S=1.2
Γ_4	$\omega\gamma$		(3.01±0.30) %	
Γ_5	$\gamma\gamma$		(2.11±0.13) %	S=1.2
Γ_6	$3\pi^0$		(1.54±0.26) × 10^{-3}	
Γ_7	$\mu^+\mu^-\gamma$		(1.03±0.26) × 10^{-4}	
Γ_8	$\pi^+\pi^-\pi^0$		< 5 %	CL=90%
Γ_9	$\pi^0\rho^0$		< 4 %	CL=90%
Γ_{10}	$\pi^+\pi^+\pi^-\pi^-$		< 1 %	CL=90%
Γ_{11}	$\pi^+\pi^+\pi^-\pi^-$ neutrals		< 1 %	CL=95%
Γ_{12}	$\pi^+\pi^+\pi^-\pi^-\pi^0$		< 1 %	CL=90%
Γ_{13}	6π		< 1 %	CL=90%
Γ_{14}	$\pi^+\pi^-e^+e^-$		< 6 × 10^{-3}	CL=90%
Γ_{15}	$\pi^0\gamma\gamma$		< 8 × 10^{-4}	CL=90%
Γ_{16}	$4\pi^0$		< 5 × 10^{-4}	CL=90%
Γ_{17}	e^+e^-		< 2.1 × 10^{-7}	CL=90%
	Charge conjugation (*C*) or Parity (*P*) violating modes			
Γ_{18}	$\pi^+\pi^-$	*P,CP*	< 2 %	CL=90%
Γ_{19}	$\pi^0\pi^0$	*P,CP*	< 9 × 10^{-4}	CL=90%
Γ_{20}	$\pi^0e^+e^-$	*C*	[a] < 1.3 %	CL=90%
Γ_{21}	ηe^+e^-	*C*	[a] < 1.1 %	CL=90%
Γ_{22}	3γ	*C*	< 1.0 × 10^{-4}	CL=90%
Γ_{23}	$\mu^+\mu^-\pi^0$	*C*	[a] < 6.0 × 10^{-5}	CL=90%
Γ_{24}	$\mu^+\mu^-\eta$	*C*	[a] < 1.5 × 10^{-5}	CL=90%

[a] *C* parity forbids this to occur as a single-photon process.

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, 2 combinations of partial widths obtained from integrated cross section, and 16 branching ratios uses 46 measurements and one constraint to determine 7 parameters. The overall fit has a $\chi^2 = 34.4$ for 40 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−49					
x_3	−62	−35				
x_4	−27	−25	34			
x_5	−22	−13	27	8		
x_6	−23	−13	36	12	10	
Γ	34	−11	−21	−3	−83	−7
	x_1	x_2	x_3	x_4	x_5	x_6

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi^+\pi^-\eta$	0.089 ±0.009	1.2
Γ_2	$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	0.061 ±0.005	1.3
Γ_3	$\pi^0\pi^0\eta$	0.042 ±0.004	1.5
Γ_4	$\omega\gamma$	0.0061 ±0.0008	1.2
Γ_5	$\gamma\gamma$	0.00427±0.00019	1.1
Γ_6	$3\pi^0$	(3.1 ±0.6) × 10^{-4}	1.1

$\eta'(958)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_5

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.27±0.19 OUR FIT Error includes scale factor of 1.1.					
4.37±0.25 OUR AVERAGE					
4.53±0.29±0.51	266	KARCH	92	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
3.61±0.13±0.48		[1] BEHREND	91	CELL	$e^+e^- \to e^+e^-\eta'(958)$
4.6 ±1.1 ±0.6	23	BARU	90	MD1	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$
4.57±0.25±0.44		BUTLER	90	MRK2	$e^+e^- \to e^+e^-\eta'(958)$
5.08±0.24±0.71	547	[2] ROE	90	ASP	$e^+e^- \to e^+e^-2\gamma$
3.8 ±0.7 ±0.6	34	AIHARA	88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.9 ±0.5 ±0.5	136	[3] WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-2\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.7 ±0.6 ±0.9	143	[4] GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.0 ±0.9		[5] BARTEL	85E	JADE	$e^+e^- \to e^+e^-2\gamma$

[1] Revaluated by us using $B(\eta' \to \rho(770)\gamma) = (30.2 \pm 1.3)\%$.

[2] Revaluated by us using $B(\eta' \to \gamma\gamma) = (2.11 \pm 0.13)\%$.

[3] Revaluated by us using $B(\eta' \to \gamma\gamma) = (2.11 \pm 0.13)\%$.

[4] Superseded by BUTLER 90.

[5] Systematic error not evaluated.

$\eta'(958)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

This combination of a partial width with the partial width into $\gamma\gamma$ and with the total width is obtained from the integrated cross section into channel(i) in the $\gamma\gamma$ annihilation.

$\Gamma(\gamma\gamma) \times \Gamma(\rho^0\gamma(\text{including non-resonant}\,\pi^+\pi^-\gamma))/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_2/\Gamma$

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.29±0.06 OUR FIT Error includes scale factor of 1.2.					
1.26±0.07 OUR AVERAGE Error includes scale factor of 1.2.					
1.09±0.04±0.13		BEHREND	91	CELL	$e^+e^- \to e^+e^-\rho(770)^0\gamma$
1.35±0.09±0.21		AIHARA	87	TPC	$e^+e^- \to e^+e^-\rho\gamma$
1.13±0.04±0.13	867	ALBRECHT	87B	ARG	$e^+e^- \to e^+e^-\rho\gamma$
1.53±0.09±0.21		ALTHOFF	84E	TASS	$e^+e^- \to e^+e^-\rho\gamma$
1.14±0.08±0.11	243	BERGER	84B	PLUT	$e^+e^- \to e^+e^-\rho\gamma$
1.73±0.34±0.35	95	JENNI	83	MRK2	$e^+e^- \to e^+e^-\rho\gamma$
1.49±0.13±0.027	213	BARTEL	82B	JADE	$e^+e^- \to e^+e^-\rho\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.85±0.31±0.24	43	BEHREND	83B	CELL	$e^+e^- \to e^+e^-\rho\gamma$

$\Gamma(\gamma\gamma) \times \Gamma(\pi^0\pi^0\eta)/\Gamma_{\rm total}$ $\Gamma_5\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.88±0.07 OUR FIT	Error includes scale factor of 1.1.			
0.92±0.06±0.11	[6] KARCH	92	CBAL	$e^+e^- \rightarrow e^+e^-\eta\pi^0\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.95±0.05±0.08	[7] KARCH	90	CBAL	$e^+e^- \rightarrow e^+e^-\eta\pi^0\pi^0$
1.00±0.08±0.10	[7,8] ANTREASYAN	87	CBAL	$e^+e^- \rightarrow e^+e^-\eta\pi^0\pi^0$

[6] Revaluated by us using B($\eta \rightarrow \gamma\gamma$) = (39.21 ± 0.34)%. Supersedes ANTREASYAN 87 and KARCH 90.

[7] Superseded by KARCH 92.

[8] Using BR($\eta \rightarrow 2\gamma$)=(38.9 ± 0.5)%.

$\eta'(958)$ α PARAMETER

$|\text{MATRIX ELEMENT}|^2 = (1+\alpha y)^2 + \alpha^2$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.058±0.013	[9] ALDE	86	GAM2	38 $\pi^- p \rightarrow n\eta 2\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID		TECN	COMMENT
−0.08 ±0.03	[9] KALBFLEISCH	74	RVUE	$\eta' \rightarrow \eta\pi^+\pi^-$

[9] May not necessarily be the same for $\eta' \rightarrow \eta\pi^+\pi^-$ and $\eta' \rightarrow \eta\pi^0\pi^0$.

$\eta'(958)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))/\Gamma_{\rm total}$ $0.714\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.313±0.011 OUR FIT	Error includes scale factor of 1.1.				
0.314±0.026	281	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^-\text{neutrals})/\Gamma_{\rm total}$ $(0.714\Gamma_1+0.286\Gamma_3+0.89\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.399±0.009 OUR FIT	Error includes scale factor of 1.1.				
0.36 ±0.05 OUR AVERAGE					
0.4 ±0.1	39	LONDON	66	HBC	2.24 $K^- p \rightarrow \Lambda\pi^+\pi^-$ neutrals
0.35 ±0.06	33	BADIER	65B	HBC	3 $K^- p$

$\Gamma(\pi^+\pi^-\eta(\text{charged decay}))/\Gamma_{\rm total}$ $0.286\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.125±0.004 OUR FIT	Error includes scale factor of 1.1.				
0.116±0.013 OUR AVERAGE					
0.123±0.014	107	RITTENBERG	69	HBC	1.7–2.7 $K^- p$
0.10 ±0.04	10	LONDON	66	HBC	2.24 $K^- p \rightarrow \Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$
0.07 ±0.04	7	BADIER	65B	HBC	3 $K^- p$

$[\Gamma(\pi^0\pi^0\eta(\text{charged decay})) + \Gamma(\omega(\text{charged decay})\gamma)]/\Gamma_{\rm total}$ $(0.286\Gamma_3+0.89\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.086±0.005 OUR FIT	Error includes scale factor of 1.2.				
0.045±0.029	42	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\text{neutrals})/\Gamma_{\rm total}$ $(0.714\Gamma_3+0.09\Gamma_4+\Gamma_5)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.172±0.009 OUR FIT	Error includes scale factor of 1.1.				
0.187±0.017 OUR AVERAGE					
0.185±0.022	535	BASILE	71	CNTR	1.6 $\pi^- p \rightarrow nX^0$
0.189±0.026	123	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\rho^0\gamma(\text{including non-resonant}\,\pi^+\pi^-\gamma))/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.302±0.013 OUR FIT	Error includes scale factor of 1.1.				
0.319±0.030 OUR AVERAGE					
0.329±0.033	298	RITTENBERG	69	HBC	1.7–2.7 $K^- p$
0.2 ±0.1	20	LONDON	66	HBC	2.24 $K^- p \rightarrow \Lambda\pi^+\pi^-\gamma$
0.34 ±0.09	35	BADIER	65B	HBC	3 $K^- p$

$\Gamma(\rho^0\gamma(\text{including non-resonant}\,\pi^+\pi^-\gamma))/\Gamma(\pi\pi\eta)$ $\Gamma_2/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.469±0.029 OUR FIT	Error includes scale factor of 1.1.			
0.31 ±0.15	DAVIS	68	HBC	5.5 $K^- p$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\rm total}$ Γ_{20}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.013	90	RITTENBERG	65	HBC	2.7 $K^- p$

$\Gamma(\eta e^+e^-)/\Gamma_{\rm total}$ Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	RITTENBERG	65	HBC	2.7 $K^- p$

$\Gamma(\pi^0\rho^0)/\Gamma_{\rm total}$ Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	RITTENBERG	65	HBC	2.7 $K^- p$

$\Gamma(\pi^+\pi^- e^+e^-)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	RITTENBERG	65	HBC	2.7 $K^- p$

$\Gamma(6\pi)/\Gamma_{\rm total}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	LONDON	66	HBC	Compilation

$\Gamma(\omega\gamma)/\Gamma(\pi^+\pi^-\eta)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.069±0.008 OUR FIT	Error includes scale factor of 1.1.				
0.068±0.013	68	ZANFINO	77	ASPK	8.4 $\pi^- p$

$\Gamma(\rho^0\gamma(\text{including non-resonant}\,\pi^+\pi^-\gamma))/[\Gamma(\pi^+\pi^-\eta) + \Gamma(\pi^0\pi^0\eta) + \Gamma(\omega\gamma)]$ $\Gamma_2/(\Gamma_1+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.448±0.028 OUR FIT	Error includes scale factor of 1.1.			
0.25 ±0.14	DAUBER	64	HBC	1.95 $K^- p$

$\Gamma(\gamma\gamma)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0211±0.0013 OUR FIT	Error includes scale factor of 1.2.				
0.0196±0.0015 OUR AVERAGE					
0.0200±0.0018		[10] STANTON	80	SPEC	8.45 $\pi^- p \rightarrow n\pi^+\pi^- 2\gamma$
0.025 ±0.007		DUANE	74	MMS	$\pi^- p \rightarrow n$MM
0.0171±0.0033	68	DALPIAZ	72	CNTR	1.6 $\pi^- p \rightarrow nX^0$
0.020 $^{+0.008}_{-0.006}$	31	HARVEY	71	OSPK	3.65 $\pi^- p \rightarrow nX^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.018 ±0.002	6000	[11] APEL	79	NICE	15–40 $\pi^- p \rightarrow n2\gamma$

[10] Includes APEL 79 result.

[11] Data is included in STANTON 80 evaluation.

$\Gamma(e^+e^-)/\Gamma_{\rm total}$ Γ_{17}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	COMMENT
<2.1	90	VOROBYEV	88	ND	$e^+e^- \rightarrow \pi^+\pi^-\eta$

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	95	DANBURG	73	HBC	2.2 $K^- p \rightarrow \Lambda X^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.05	90	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	95	DANBURG	73	HBC	2.2 $K^- p \rightarrow \Lambda X^0$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\text{neutrals})/\Gamma_{\rm total}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	95	DANBURG	73	HBC	2.2 $K^- p \rightarrow \Lambda X^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^0\pi^0\eta(3\pi^0\,\text{decay}))/\Gamma_{\rm total}$ $0.321\Gamma_3/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.066±0.004 OUR FIT	Error includes scale factor of 1.2.				
0.11 ±0.06	4	BENSINGER	70	DBC	2.2 $\pi^+ d$

$\Gamma(\rho^0\gamma(\text{including non-resonant}\,\pi^+\pi^-\gamma))/\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))$ $\Gamma_2/0.714\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.97±0.07 OUR FIT	Error includes scale factor of 1.1.				
1.01±0.09 OUR AVERAGE					
1.07±0.17		BELADIDZE	92C	VES	36 π^- Be $\rightarrow \pi^-\eta'\eta$ Be
0.92±0.14	473	DANBURG	73	HBC	2.2 $K^- p \rightarrow \Lambda X^0$
1.11±0.18	192	JACOBS	73	HBC	2.9 $K^- p \rightarrow \Lambda X^0$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta(\text{neutral decay}))$ $\Gamma_5/0.714\Gamma_3$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.143±0.010 OUR FIT	Error includes scale factor of 1.6.				
0.188±0.058	16	APEL	72	OSPK	3.8 $\pi^- p \rightarrow nX^0$

$\Gamma(\mu^+\mu^-\gamma)/\Gamma(\gamma\gamma)$ Γ_7/Γ_5

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
4.9±1.2	33	VIKTOROV 80	CNTR	25,33 $\pi^- p \to 2\mu\gamma$

$\Gamma(\mu^+\mu^-\eta)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
<1.5	90	DZHELYADIN 81	CNTR	30 $\pi^- p \to \eta' n$

$\Gamma(\mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
<6.0	90	DZHELYADIN 81	CNTR	30 $\pi^- p \to \eta' n$

$\Gamma(3\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_6/Γ_3

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
74±12 OUR FIT			
74±12 OUR AVERAGE			
74±15	ALDE 87B	GAM2	38 $\pi^- p \to n6\gamma$
75±18	BINON 84	GAM2	30–40 $\pi^- p \to n6\gamma$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_5/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.102±0.007 OUR FIT Error includes scale factor of 1.6.			
0.105±0.010 OUR AVERAGE Error includes scale factor of 1.9.			
0.091±0.009	AMSLER 93	CBAR	0.0 $\overline{p}p$
0.112±0.002±0.006	ALDE 87B	GAM2	38 $\pi^- p \to n2\gamma$

$\Gamma(\omega\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.146±0.014 OUR FIT			
0.147±0.016	ALDE 87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(3\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_{22}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<4.6	90	ALDE 87B	GAM2	38 $\pi^- p \to n3\gamma$

$\Gamma(\pi^0\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_{15}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<37	90	ALDE 87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_{19}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<45	90	ALDE 87B	GAM2	38 $\pi^- p \to n4\gamma$

$\Gamma(4\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_{16}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<23	90	ALDE 87B	GAM2	38 $\pi^- p \to n8\gamma$

$\eta'(958)$ *C*-NONCONSERVING DECAY PARAMETER

See the note on η decay parameters in the Stable Particle Particle Listings for definition of this parameter.

DECAY ASYMMETRY PARAMETER FOR $\pi^+\pi^-\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.01 ±0.04 OUR AVERAGE				
−0.019±0.056		AIHARA 87	TPC	$2\gamma \to \pi^+\pi^-\gamma$
−0.069±0.078	295	GRIGORIAN 75	STRC	2.1 $\pi^- p$
0.00 ±0.10	103	KALBFLEISCH 75	HBC	2.18 $K^- p \to \Lambda\pi^+\pi^-\gamma$
0.07 ±0.08	152	RITTENBERG 65	HBC	2.1–2.7 $K^- p$

$\eta'(958)$ REFERENCES

WURZINGER	96	PL B374 283	+Siebert+	(BONN, ORSAY, SACL, CRAC)
AMSLER	93	ZPHY C58 175	+Armstrong, Merkel+	(Crystal Barrel Collab.)
BELADIDZE	92C	SJNP 55 1535 Translated from YAF 55 2748.	+Bityukov, Borisov	(SERP, TBIL)
KARCH	92	ZPHY C54 33	+Antreasyan, Bartels+	(Crystal Ball Collab.)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BARU	90	ZPHY C48 581	+Blinov, Blinov+	(MD-1 Collab.)
BUTLER	90	PR D42 1368	+Boyer+	(Mark II Collab.)
KARCH	90	PL B249 353	+Antreasyan, Bartels+	(Crystal Ball Collab.)
ROE	90	PR D41 17	+Bartha, Burke, Garbincius+	(ASP Collab.)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
AIHARA	87	PR D35 2650	+Alston-Garnjost+	(TPC-2γ Collab.) JP
ALBRECHT	87B	PL B199 457	+Andam, Binder+	(ARGUS Collab.)
ALDE	87B	ZPHY C36 603	+Binon, Bricman+	(LANL, BELG, SERP, LAPP)
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
ALDE	86	PL B177 115	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
BARTEL	85E	PL 160B 421	+Becker, Cords, Felst+	(JADE Collab.)
ALTHOFF	84E	PL 147B 487	+Braunschweig, Kirschfink, Luebelsmeyer+	(TASSO Collab.)
BERGER	84B	PL 142B 125		(PLUTO Collab.)
BINON	84	PL 140B 264	+Donskov, Duteil+	(SERP, BELG, LAPP, CERN)
BEHREND	83B	PL 125B 518	+D'Agostini+	(CELLO Collab.)
Also	82C	PL 114B 378	Behrend, Chen, Fenner, Field+	(CELLO Collab.)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BARTEL	82B	PL 113B 190	+Cords+	(JADE Collab.)
DZHELYADIN	81	PL 105B 239	+Golovkin, Konstantinov, Kubarovski+	(SERP)
STANTON	80	PL 92 B 353	+Edwards, Legacey+	(OSU, CARL, MCGI, TNTO)
VIKTOROV	80	SJNP 32 520 Translated from YAF 32 1005.	+Golovkin, Dzhelyadin, Zaitsev, Mukhin+	(SERP)
APEL	79	PL 83B 131	Augenstein, Bertolucci	(KARLK, KARLE, PISA, SERP, WIEN)
BINNIE	79	PL 83B 141	+Carr, Debenham, Jones, Karami, Keyne+	(LOIC)
ZANFINO	77	PRL 38 930	+Brockman+	(CARL, MCGI, OHIO, TNTO)
GRIGORIAN	75	NP B91 232	+Ladage, Mellema, Rudnick+	(+)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
DUANE	74	PRL 32 425	+Binnie, Camilleri, Carr+	(LOIC, SHMP)
KALBFLEISCH	74	PR D10 916		(BNL)
DANBURG	73	PR D8 3744	+Kalbfleisch, Borenstein, Chapman+	(BNL, MICH) JP
JACOBS	73	PR D8 18	+Chang, Gauthier+	(BRAN, UMD, SYRA, TUFTS) JP
APEL	72	PL 40B 680	+Auslander, Muller, Bertolucci+	(KARLK, KARLE, PISA)
DALPIAZ	72	PL 42B 377	+Frabetti, Massam, Navarria, Zichichi	(CERN)
BASILE	71	NC 3A 371	+Bollini, Dalpiaz, Frabetti+	(CERN, BGNA, STRB)
HARVEY	71	PRL 27 885	+Marquit, Peterson, Rhoades+	(MINN, MICH)
BENSINGER	70	PL 33B 505	+Erwin, Thompson, Walker	(WISC)
RITTENBERG	69	Thesis UCRL 18863		(LRL) I
DAVIS	68	PL 27B 532	+Ammar, Mott, Dagan, Derrick+	(NWES, ANL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJP
BADIER	65B	PL 17 337	+Demoulin, Barloutaud+	(EPOL, SACL, AMST)
RITTENBERG	65	PRL 15 556	+Kalbfleisch	(LRL, BNL)
DAUBER	64	PRL 13 449	+Slater, Smith, Stork, Ticho	(UCLA) JP

OTHER RELATED PAPERS

GRONBERG	98	PR D57 33	J. Gronberg, Hill, Kutschke+	(CLEO Collab.)
ABELE	97B	PL B402 195	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
GENOVESE	94	ZPHY C61 425	+Lichtenberg, Pedrazzi	(TORI, IND)
BENAYOUN	93	ZPHY 58 31	+Feindt, Girone+	(CDEF, CERN, BARI)
KAMAL	92	PL B284 421	+Xu	(ALBE)
BICKERSTAFF	82	ZPHY C16 171	+McKellar	(MELB)
KIENZLE	65	PL 19 438	+Maglich, Levrat, Lefebvres+	(CERN)
TRILLING	65	PL 19 427	+Brown, Goldhaber, Kadyk, Scanlo	(LRL)
GOLDBERG	64	PRL 12 546	+Gundzik, Lichtman, Connolly, Hart+	(SYRA, BNL)
GOLDBERG	64B	PRL 13 249	+Gundzik, Leitner, Connolly, Hart+	(SYRA, BNL)
KALBFLEISCH	64	PRL 12 527	+Alvarez, Barbaro-Galtieri+	(LRL) JP
KALBFLEISCH	64B	PRL 13 349	+Dahl, Rittenberg	(LRL) JP

$f_0(980)$

$I^G(J^{PC}) = 0^+(0^{++})$

See also the minireview on scalar mesons under $f_0(1370)$. (See the index for the page number.)

$f_0(980)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
980 ±10 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
955 ±10		[1] ALDE 97	GAM2	450 $pp \to pp\pi^0\pi^0$
994 ± 9		[2] BERTIN 97C	OBLX	0.0 $\overline{p}p \to \pi^+\pi^-\pi^0$
993.2± 6.5±6.9		[3] ISHIDA 96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
1006		TORNQVIST 96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
997 ± 5	3k	[4] ALDE 95B	GAM2	38 $\pi^- p \to \pi^0\pi^0 n$
960 ±10	10k	[5] ALDE 95B	GAM2	38 $\pi^- p \to \pi^0\pi^0 n$
994 ± 5		AMSLER 95B	CBAR	0.0 $\overline{p}p \to 3\pi^0$
~ 996		[6] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
987 ± 6		[7] ANISOVICH 95	RVUE	
1015		JANSSEN 95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
983		[8] BUGG 94	RVUE	$\overline{p}p \to \eta 2\pi^0$
973 ± 2		KAMINSKI 94	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
988		[9] ZOU 94B	RVUE	
988 ±10		[10] MORGAN 93	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K}), J/\psi \to \phi\pi\pi(K\overline{K}), D_s \to \pi(\pi\pi)$
971.1± 4.0		[1] AGUILAR-... 91	EHS	400 pp
979 ± 4		[11] ARMSTRONG 91	OMEG	300 $pp \to pp\pi\pi, ppK\overline{K}$
956 ±12		BREAKSTONE 90	SFM	$pp \to pp\pi^+\pi^-$
959.4± 6.5		[1] AUGUSTIN 89	DM2	$J/\psi \to \omega\pi^+\pi^-$
978 ± 9		[1] ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^- X$
$985.0^{+9.0}_{-39.0}$		ETKIN 82B	MPS	23 $\pi^- p \to n2K^0_S$
974 ± 4		[11] GIDAL 81	MRK2	$J/\psi \to \pi^+\pi^- X$
975		[12] ACHASOV 80	RVUE	
986 ±10		[11] AGUILAR-... 78	HBC	0.7 $\overline{p}p \to K^0_S K^0_S$
969 ± 5		[11] LEEPER 77	ASPK	2–2.4 $\pi^- p \to \pi^+\pi^- n, K^+K^- n$
987 ± 7		[11] BINNIE 73	CNTR	$\pi^- p \to n MM$
1012 ± 6		[13] GRAYER 73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
1007 ±20		[13] HYAMS 73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
997 ± 6		[13] PROTOPOP... 73	HBC	7 $\pi^+ p \to \pi^+ p\pi^+\pi^-$

[1] From invariant mass fit.
[2] On sheet II in a 2 pole solution. The other pole is found on sheet III at (963-29i) MeV.
[3] Reanalysis of data from HYAMS 73, GRAYER 74, SRINIVASAN 75, and ROSSELET 77 using the interfering amplitude method.
[4] At high $|t|$.
[5] At low $|t|$.
[6] On sheet II in a 4-pole solution, the other poles are found on sheet III at $(953-55i)$ MeV and on sheet IV at $(938-35i)$ MeV.
[7] Combined fit of ALDE 95B, ANISOVICH 94, AMSLER 94D.
[8] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(996-103i)$ MeV.
[9] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(797-185i)$ MeV and can be interpreted as a shadow pole.
[10] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(978-28i)$ MeV.
[11] From coupled channel analysis.
[12] Coupled channel analysis with finite width corrections.
[13] Included in AGUILAR-BENITEZ 78 fit.

$f_0(980)$ WIDTH

Width determination very model dependent. Peak width in $\pi\pi$ is about 50 MeV, but decay width can be much larger.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
40 to 100 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
69 ± 15		[14] ALDE 97	GAM2	$450\ pp \to pp\pi^0\pi^0$
38 ± 20		[15] BERTIN 97C	OBLX	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
~ 100		[16] ISHIDA 96	RVUE	$\pi\pi \to \pi\pi, K\bar{K}$
34		TORNQVIST 96	RVUE	$\pi\pi \to \pi\pi, K\bar{K}, K\pi, \eta\pi$
48 ± 10	3k	[17] ALDE 95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
95 ± 20	10k	[18] ALDE 95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
26 ± 10		AMSLER 95B	CBAR	$0.0\ \bar{p}p \to 3\pi^0$
~ 112		[19] AMSLER 95D	CBAR	$0.0\ \bar{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
80 ± 12		[20] ANISOVICH 95	RVUE	
30		JANSSEN 95	RVUE	$\pi\pi \to \pi\pi, K\bar{K}$
74		[21] BUGG 94	RVUE	$\bar{p}p \to \eta 2\pi^0$
29 ± 2		KAMINSKI 94	RVUE	$\pi\pi \to \pi\pi, K\bar{K}$
46		[22] ZOU 94B	RVUE	
48 ± 12		[23] MORGAN 93	RVUE	$\pi\pi(K\bar{K}) \to \pi\pi(K\bar{K}), J/\psi \to \phi\pi\pi(K\bar{K}), D_s \to \pi(\pi\pi)$
37.4 ± 10.6		[14] AGUILAR-... 91	EHS	$400\ pp$
72 ± 8		[24] ARMSTRONG 91	OMEG	$300\ pp \to pp\pi\pi, ppK\bar{K}$
110 ± 30		BREAKSTONE 90	SFM	$pp \to pp\pi^+\pi^-$
29 ± 13		[14] ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^- X$
120 ± 281 ± 20		ETKIN 82B	MPS	$23\ \pi^- p \to n2K^0_S$
28 ± 10		[24] GIDAL 81	MRK2	$J/\psi \to \pi^+\pi^- X$
70 to 300		[25] ACHASOV 80	RVUE	
100 ± 80		[26] AGUILAR-... 78	HBC	$0.7\ \bar{p}p \to K^0_S K^0_S$
30 ± 8		[24] LEEPER 77	ASPK	$2\text{–}2.4\ \pi^- p \to \pi^+\pi^- n, K^+K^- n$
48 ± 14		[24] BINNIE 73	CNTR	$\pi^- p \to n MM$
32 ± 10		[27] GRAYER 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
30 ± 10		[27] HYAMS 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
54 ± 16		[27] PROTOPOP... 73	HBC	$7\ \pi^+ p \to \pi^+ p\pi^+\pi^-$

[14] From invariant mass fit.
[15] On sheet II in a 2 pole solution. The other pole is found on sheet III at (963-29i) MeV.
[16] Reanalysis of data from HYAMS 73, GRAYER 74, SRINIVASAN 75, and ROSSELET 77 using the interfering amplitude method.
[17] At high $|t|$.
[18] At low $|t|$.
[19] On sheet II in a 4-pole solution, the other poles are found on sheet III at $(953-55i)$ MeV and on sheet IV at $(938-35i)$ MeV.
[20] Combined fit of ALDE 95B, ANISOVICH 94,
[21] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(996-103i)$ MeV.
[22] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(797-185i)$ MeV and can be interpreted as a shadow pole.
[23] On sheet II in a 2 pole solution. The other pole is found on sheet III at $(978-28i)$ MeV.
[24] From coupled channel analysis.
[25] Coupled channel analysis with finite width corrections.
[26] From coupled channel fit to the HYAMS 73 and PROTOPOPESCU 73 data. With a simultaneous fit to the $\pi\pi$ phase-shifts, inelasticity and to the $K^0_S K^0_S$ invariant mass.
[27] Included in AGUILAR-BENITEZ 78 fit.

$f_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	dominant	
Γ_2	$K\bar{K}$	seen	
Γ_3	$\gamma\gamma$	$(1.19\pm0.33)\times10^{-5}$	
Γ_4	e^+e^-	$<3\ \times10^{-7}$	90%

$f_0(980)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_3

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
0.56±0.11 OUR AVERAGE				
0.63±0.14		[28] MORGAN 90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
0.42±0.06±0.18	60	[29] OEST 90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29±0.07±0.12		[30,31] BOYER 90	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
0.31±0.14±0.09		[30,31] MARSISKE 90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0$

[28] From amplitude analysis of BOYER 90 and MARSISKE 90, data corresponds to resonance parameters $m = 989$ MeV, $\Gamma = 61$ MeV.
[29] OEST 90 quote systematic errors $^{+0.08}_{-0.18}$. We use ±0.18.
[30] From analysis allowing arbitrary background unconstrained by unitarity.
[31] Data included in MORGAN 90 analysis.

$\Gamma(e^+e^-)$ Γ_4

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<8.4	90	VOROBYEV 88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(980)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/[\Gamma(\pi\pi)+\Gamma(K\bar{K})]$ $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.67±0.09	[32] LOVERRE 80	HBC	$4\ \pi^- p \to n2K^0_S$
$0.81^{+0.09}_{-0.04}$	[32] CASON 78	STRC	$7\ \pi^- p \to n2K^0_S$
0.78±0.03	[32] WETZEL 76	OSPK	$8.9\ \pi^- p \to n2K^0_S$

[32] Measure $\pi\pi$ elasticity assuming two resonances coupled to the $\pi\pi$ and $K\bar{K}$ channels only.

$f_0(980)$ REFERENCES

ALDE 97 PL B397 350 +Bellazzini, Binon+ (GAMS Collab.)
BERTIN 97C PL B408 476 A. Bertin, Bruschi+ (OBELIX Collab.)
ISHIDA 96 PTP 95 745 S. Ishida+ (TOKY, MIYA, KEK)
TORNQVIST 96 PRL 76 1575 +Roos (HELS)
ALDE 95B ZPHY C66 375 +Binon, Boutemeur+ (GAMS Collab.)
AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 95 PL B355 363 +Kondashov+ (PNPI, SERP)
JANSSEN 95 PR D52 2690 +Pearce, Holinde, Speth (STON, ADLD, JULI)
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
BUGG 94 PR D50 4412 +Anisovich+ (LOQM)
KAMINSKI 94 PR D50 3145 R. Kaminski+ (CRAC, IPN)
ZOU 94B PR D50 591 +Bugg (LOQM)
MORGAN 93 PR D48 1185 +Pennington (RAL, DURH)
AGUILAR-... 91 ZPHY C50 405 Aguilar-Benitez, Allison, Batalor+ (LEBC-EHS Collab.)
ARMSTRONG 91 ZPHY C51 351 +Benayoun+ (ATHU, BARI, BIRM, CERN, CDEF)
BOYER 90 PR D42 1350 +Butler+ (Mark II Collab.)
BREAKSTONE 90 ZPHY C48 569 + (ISU, BGNA, CERN, DORT, HEIDH, WARS)
MARSISKE 90 PR D41 3324 +Antreasyan+ (Crystal Ball Collab.)
MORGAN 90 ZPHY C48 623 +Pennington (RAL, DURH)
OEST 90 ZPHY C47 343 +Olsson+ (JADE Collab.)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
ABACHI 86B PRL 57 1990 +Derrick, Blockus+ (PURD, ANL, IND, MICH, LBL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
GIDAL 81 PL 107B 153 +Goldhaber, Guy, Millikan, Abrams+ (SLAC, LBL)
ACHASOV 80 SJNP 32 566 +Devyanin, Shestakov (NOVM)
Translated from YAF 32 1098.
LOVERRE 80 ZPHY C6 187 +Armenteros, Dionisi+ (CERN, CDEF, MADR, STOH) IJP
AGUILAR-... 78 NP B140 73 Aguilar-Benitez, Cerrada+ (MADR, BOMB, CERN+)
CASON 78 PRL 41 271 +Baumbaugh, Bishop, Biswas+ (NDAM, ANL)
LEEPER 77 PR D16 2054 +Buttram, Crawley, Duke, Lamb, Peterson (ISU)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
WETZEL 76 NP B115 208 +Freudenreich, Beusch+ (ETH, CERN, LOIC)
SRINIVASAN 75 PR D12 681 +Helland, Lennox, Klem+ (NDAM, ANL)
GRAYER 74 NP B75 189 +Hyams, Blum, Dietl+ (CERN, MPIM)
BINNIE 73 PRL 31 1534 +Carr, Debenham, Duane, Garbutt+ (LOIC, SHMP)
GRAYER 73 Tallahassee +Hyams, Jones, Blum, Dietl, Koch+ (CERN, MPIM)
HYAMS 73 NP B64 134 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
PROTOPOP... 73 PR D7 1279 Protopopescu, Alston-Garnjost, Galtieri, Flatte+ (LBL)

OTHER RELATED PAPERS

ACHASOV 97C PR D56 4084 N.N. Achasov+
ACHASOV 97D PR D56 203 N.N. Achasov+
PROKOSHKIN 97 SPD 42 117 +Kondashov, Sadovsky+ (SERP)
Translated from DANS 353 323.
AU 87 PR D35 1633 +Morgan, Pennington (DURH, RAL)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
MENNESSIER 83 ZPHY C16 241 (MONP)
BARBER 82 ZPHY C12 1 +Dainton, Brodbeck, Brookes+ (DARE, LANC, SHEF)
ETKIN 82C PR D25 2446 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
SRINIVASAN 75 PR D12 681 +Helland, Lennox, Klem+ (NDAM, ANL)
BIGI 62 CERN Conf. 247 +Brandt, Carrara+ (CERN)
BINGHAM 62 CERN Conf. 240 +Bloch+ (EPOL, CERN)
ERWIN 62 PRL 9 34 +Hoyer, March, Walker, Wangler (WISC, BNL)
WANG 61 JETP 13 323 +Veksler, Vrana+ (JINR)
Translated from ZETF 40 464.

$a_0(980)$

$I^G(J^{PC}) = 1^-(0^{++})$

See our minireview on scalar mesons under $f_0(1370)$. (See the index for the page number.)

$a_0(980)$ MASS

VALUE (MeV)	*DOCUMENT ID*
983.4±0.9 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

$\eta\pi$ FINAL STATE ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.					
983.7 ± 0.9 OUR AVERAGE					
984.45± 1.23±0.34		AMSLER 94C	CBAR		0.0 $\overline{p}p \rightarrow \omega\eta\pi^0$
982 ± 2		[1] AMSLER 92	CBAR		0.0 $\overline{p}p \rightarrow \eta\eta\pi^0$
984 ± 4	1040	[1] ARMSTRONG 91B	OMEG	±	300 $pp \rightarrow pp\eta\pi^+\pi^-$
976 ± 6		ATKINSON 84E	OMEG	±	25–55 $\gamma p \rightarrow \eta\pi n$
986 ± 3	500	[2] EVANGELISTA 81	OMEG	±	12 $\pi^- p \rightarrow \eta\pi^+\pi^-\pi^- p$
990 ± 7	145	[2] GURTU 79	HBC	±	4.2 $K^- p \rightarrow \Lambda\eta 2\pi$
977 ± 7		GRASSLER 77	HBC	−	16 $\pi^\mp p \rightarrow p\eta 3\pi$
972 ±10	150	DEFOIX 72	HBC	±	0.7 $\overline{p}p \rightarrow 7\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
987		TORNQVIST 96	RVUE		$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
991		JANSSEN 95	RVUE		$\eta\pi \rightarrow \eta\pi, K\overline{K}, K\pi, \eta\pi$
980 ±11	47	CONFORTO 78	OSPK	−	4.5 $\pi^- p \rightarrow pX^-$
978 ±16	50	CORDEN 78	OMEG	±	12–15 $\pi^- p \rightarrow n\eta 2\pi$
989 ± 4	70	WELLS 75	HBC	−	3.1–6 $K^- p \rightarrow \Lambda\eta 2\pi$
970 ±15	20	BARNES 69C	HBC	−	4–5 $K^- p \rightarrow \Lambda\eta 2\pi$
980 ±10		CAMPBELL 69	DBC	±	2.7 $\pi^+ d$
980 ±10	15	MILLER 69B	HBC	−	4.5 $K^- N \rightarrow \eta\pi\Lambda$
980 ±10	30	AMMAR 68	HBC	±	5.5 $K^- p \rightarrow \Lambda\eta 2\pi$

[1] From a single Breit-Wigner fit.

[2] From $f_1(1285)$ decay.

$K\overline{K}$ ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.					
980.8± 2.7 OUR AVERAGE					
982 ± 3		[3] ABELE 98	CBAR		0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
976 ± 6	316	DEBILLY 80	HBC	±	1.2–2 $\overline{p}p \rightarrow f_1(1285)\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1016 ±10	100	[4] ASTIER 67	HBC	±	0.0 $\overline{p}p$
1003.3± 7.0	143	[5] ROSENFELD 65	RVUE	±	

[3] T-matrix pole on sheet II, the pole on sheet III is at 1006-i49 MeV.

[4] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.

[5] Plus systematic errors.

$a_0(980)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
50 to 100 OUR ESTIMATE		Width determination very model dependent. Peak width in $\eta\pi$ is about 60 MeV, but decay width can be much larger.			
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 100		TORNQVIST 96	RVUE		$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
202		JANSSEN 95	RVUE		$\eta\pi \rightarrow \eta\pi, K\overline{K}, K\pi, \eta\pi$
54.12± 0.34±0.12		AMSLER 94C	CBAR		0.0 $\overline{p}p \rightarrow \omega\eta\pi^0$
54 ±10		[6] AMSLER 92	CBAR		0.0 $\overline{p}p \rightarrow \eta\eta\pi^0$
95 ±14	1040	[6] ARMSTRONG 91B	OMEG	±	300 $pp \rightarrow pp\eta\pi^+\pi^-$
62 ±15	500	[7] EVANGELISTA 81	OMEG	±	12 $\pi^- p \rightarrow \eta\pi^+\pi^-\pi^- p$
60 ±20	145	[7] GURTU 79	HBC	±	4.2 $K^- p \rightarrow \Lambda\eta 2\pi$
60 $^{+50}_{-30}$	47	CONFORTO 78	OSPK	−	4.5 $\pi^- p \rightarrow pX^-$
86.0 $^{+60.0}_{-50.0}$	50	CORDEN 78	OMEG	±	12–15 $\pi^- p \rightarrow n\eta 2\pi$
44 ±22		GRASSLER 77	HBC	−	16 $\pi^\mp p \rightarrow p\eta 3\pi$
80 to 300		[8] FLATTE 76	RVUE	−	4.2 $K^- p \rightarrow \Lambda\eta 2\pi$
16.0 $^{+25.0}_{-16.0}$	70	WELLS 75	HBC	−	3.1–6 $K^- p \rightarrow \Lambda\eta 2\pi$
30 ± 5	150	DEFOIX 72	HBC	±	0.7 $\overline{p}p \rightarrow 7\pi$
40 ±15		CAMPBELL 69	DBC	±	2.7 $\pi^+ d$
60 ±30	15	MILLER 69B	HBC	−	4.5 $K^- N \rightarrow \eta\pi\Lambda$
80 ±30	30	AMMAR 68	HBC	±	5.5 $K^- p \rightarrow \Lambda\eta 2\pi$

[6] From a single Breit-Wigner fit.

[7] From $f_1(1285)$ decay.

[8] Using a two-channel resonance parametrization of GAY 76B data.

$K\overline{K}$ ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
92± 8		[9] ABELE 98	CBAR		0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 25	100	[10] ASTIER 67	HBC	±	
57±13	143	[11] ROSENFELD 65	RVUE	±	

[9] T-matrix pole on sheet II, the pole on sheet III is at 1006-i49 MeV.

[10] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.

[11] Plus systematic errors.

$a_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	dominant
Γ_2	$K\overline{K}$	seen
Γ_3	$\rho\pi$	
Γ_4	$\gamma\gamma$	seen
Γ_5	e^+e^-	

$a_0(980)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.24^{+0.08}_{-0.07}$ OUR AVERAGE				
0.28±0.04±0.10	44	OEST 90	JADE	$e^+e^- \rightarrow e^+e^-\pi^0\eta$
0.19±0.07$^{+0.10}_{-0.07}$		ANTREASYAN 86	CBAL	$e^+e^- \rightarrow e^+e^-\pi^0\eta$

$\Gamma(\eta\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_5/\Gamma$

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.5	90	VOROBYEV 88	ND	$e^+e^- \rightarrow \pi^0\eta$

$a_0(980)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\pi)$ — Γ_2/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.23±0.05	[12] ABELE 98	CBAR		0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.16±0.18	[13] BUGG 94	RVUE		$\overline{p}p \rightarrow \eta\eta\pi^0$
0.7 ±0.3	[14] CORDEN 78	OMEG		12–15 $\pi^- p \rightarrow n\eta 2\pi$
0.25±0.08	[14] DEFOIX 72	HBC	±	0.7 $\overline{p} \rightarrow 7\pi$

[12] Using $\pi^0\pi^0\eta$ from AMSLER 94D.

[13] BUGG 94 uses AMSLER 94C data. This is a ratio of couplings.

[14] From the decay of $f_1(1285)$.

$\Gamma(\rho\pi)/\Gamma(\eta\pi)$ — Γ_3/Γ_1

$\rho\pi$ forbidden.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	70	AMMAR 70	HBC	±	4.1,5.5 $K^- p \rightarrow \Lambda\eta 2\pi$

$a_0(980)$ REFERENCES

ABELE	98	PR D57 3860	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
AMSLER	94C	PL B327 425	+Armstrong, Ravndal+	(Crystal Barrel Collab.)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
AMSLER	92	PL B291 347	+Augustin, Baker+	(Crystal Barrel Collab.)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
DEBILLY	80	NP B176 1	+Briand, Duboc, Levy+	(CURIN, LAUS, NEUC, GLAS)
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)
CONFORTO	78	LNC 23 419	+Conforto, Key+	(RHEL, TNTO, CHIC, FNAL+)
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
GRASSLER	77	NP B121 189	+	(AACH3, BERL, BONN, CERN, CRAC, HEIDH+)
FLATTE	76	PL 63B 224		(CERN)
GAY	76B	PL 63B 220	+Chaloupka, Blokzijl, Heinen+	(CERN, AMST, NIJM) JP
WELLS	75	NP B101 333	+Radojicic, Roscoe, Lyons	(OXF)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
AMMAR	70	PR D2 430	+Kropac, Davis+	(KANS, NWES, ANL, WISC)
BARNES	69C	PRL 23 610	+Chung, Eisner, Bassano, Goldberg+	(BNL, SYRA)
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)
MILLER	69B	PL 29B 255	+Kramer, Carmony+	(PURD)
Also	69	PR 188 2011	Yen, Ammann, Carmony, Eisner+	(PURD)
AMMAR	68	PRL 21 1832	+Davis, Kropac, Derrick, Fields+	(NWES, ANL)
ASTIER	67	PL 25B 294 Includes data of BARLOW 67, CONFORTO 67, and ARMENTEROS 65.	+Montanet, Baubillier, Duboc+	(CDEF, CERN, IRAD)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)
ARMENTEROS	65	PL 17 344	+Edwards, Jacobsen+	(CERN, CDEF)
ROSENFELD	65	Oxford Conf. 58		(LRL)

OTHER RELATED PAPERS

ACHASOV	97C	PR D56 4084	N.N. Achasov+	
ACHASOV	97D	PR D56 203	N.N. Achasov+	
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
TORNQVIST	90	NPBPS 21 196		(HELS)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ACHASOV	88B	ZPHY C41 309	+Shestakov	(NOVM)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
TORNQVIST	82	PRL 49 624		(HELS)
BRAMON	80	PL 93B 65	+Masso	(BARC)
TURKOT	63	Siena Conf. 1 661	+Collins, Fujii, Kemp+	(BNL, PITT)

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

ϕ(1020) MASS

We average mass and width values only when the systematic errors have been evaluated.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1019.413±0.008 OUR AVERAGE				
1019.42 ±0.06	55600	AKHMETSHIN 95	CMD2	$e^+e^- \to$ hadrons
1019.7 ±0.3	2012	DAVENPORT 86	MPSF	400 $pA \to 4KX$
1019.411±0.008	642k	[1] DIJKSTRA 86	SPEC	100–200 $\pi^{\pm}$, $\overline{p}$, p, $K^{\pm}$, on Be
1019.7 ±0.1 ±0.1	5079	ALBRECHT 85D	ARG	10 $e^+e^- \to K^+K^-X$
1019.3 ±0.1	1500	ARENTON 82	AEMS	11.8 polar. $pp \to KK$
1019.67 ±0.17	25080	[2] PELLINEN 82	RVUE	
1019.52 ±0.13	3681	BUKIN 78C	OLYA	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1019.8 ±0.7		ARMSTRONG 86	OMEG	85 $\pi^+/pp \to \pi^+/p4Kp$
1020.1 ±0.11	5526	[3] ATKINSON 86	OMEG	20–70 γp
1019.7 ±1.0		BEBEK 86	CLEO	$e^+e^- \to \Upsilon(4S)$
1020.9 ±0.2		[3] FRAME 86	OMEG	13 $K^+p \to \phi K^+p$
1021.0 ±0.2		[3] ARMSTRONG 83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1020.0 ±0.5		[3] ARMSTRONG 83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1019.7 ±0.3		[3] BARATE 83	GOLI	190 $\pi^-\mathrm{Be} \to 2\mu X$
1019.8 ±0.2 ±0.5	766	IVANOV 81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
1019.4 ±0.5	337	COOPER 78B	HBC	0.7–0.8 $\overline{p}p \to K^0_S K^0_L \pi^+\pi^-$
1020 ±1	383	[3] BALDI 77	CNTR	10 $\pi^-p \to \pi^-\phi p$
1018.9 ±0.6	800	COHEN 77	ASPK	6 $\pi^{\pm}N \to K^+K^-N$
1019.7 ±0.5	454	KALBFLEISCH 76	HBC	2.18 $K^-p \to \Lambda K\overline{K}$
1019.4 ±0.8	984	BESCH 74	CNTR	2 $\gamma p \to pK^+K^-$
1020.3 ±0.4	100	BALLAM 73	HBC	2.8–9.3 γp
1019.4 ±0.7		BINNIE 73B	CNTR	$\pi^-p \to \phi n$
1019.6 ±0.5	120	[4] AGUILAR-... 72B	HBC	3.9,4.6 $K^-p \to \Lambda K^+K^-$
1019.9 ±0.5	100	[4] AGUILAR-... 72B	HBC	3.9,4.6 $K^-p \to K^-pK^+K^-$
1020.4 ±0.5	131	COLLEY 72	HBC	10 $K^+p \to K^+p\phi$
1019.9 ±0.3	410	STOTTLE... 71	HBC	2.9 $K^-p \to \Sigma/\Lambda K\overline{K}$

[1] Weighted and scaled average of 12 measurements of DIJKSTRA 86.
[2] PELLINEN 82 review includes AKERLOF 77, DAUM 81, BALDI 77, AYRES 74, DEGROOT 74.
[3] Systematic errors not evaluated.
[4] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

ϕ(1020) WIDTH

We average mass and width values only when the systematic errors have been evalutated.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
4.43±0.05 OUR AVERAGE				
4.44±0.09	55600	AKHMETSHIN 95	CMD2	$e^+e^- \to$ hadrons
4.45±0.06	271k	DIJKSTRA 86	SPEC	100 π^- Be
4.5 ±0.7	1500	ARENTON 82	AEMS	11.8 polar. $pp \to KK$
4.2 ±0.6	766	[5] IVANOV 81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
4.3 ±0.6		[5] CORDIER 80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
4.36±0.29	3681	[5] BUKIN 78C	OLYA	$e^+e^- \to$ hadrons
4.4 ±0.6	984	[5] BESCH 74	CNTR	2 $\gamma p \to pK^+K^-$
4.67±0.72	681	[5] BALAKIN 71	OSPK	$e^+e^- \to$ hadrons
4.09±0.29		BIZOT 70	OSPK	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.6 ±0.8	337	[5] COOPER 78B	HBC	0.7–0.8 $\overline{p}p \to K^0_S K^0_L \pi^+\pi^-$
4.5 ±0.50	1300	[5,6] AKERLOF 77	SPEC	400 $pA \to K^+K^-X$
4.5 ±0.8	500	[5,6] AYRES 74	ASPK	3–6 $\pi^-p \to K^+K^-n$, $K^-p \to K^+K^-\Lambda/\Sigma^0$
3.81±0.37		COSME 74B	OSPK	$e^+e^- \to K^0_L K^0_S$
3.8 ±0.7	454	[5] BORENSTEIN 72	HBC	2.18 $K^-p \to K\overline{K}n$

[5] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[6] Systematic errors not evaluated.

ϕ(1020) DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ±0.8) %	S=1.3
Γ_2	$K^0_L K^0_S$	(34.1 ±0.6) %	S=1.2
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.5 ±0.7) %	S=1.5
Γ_4	$\rho\pi$		
Γ_5	$\pi^+\pi^-\pi^0$		
Γ_6	$\eta\gamma$	(1.26±0.06) %	S=1.1
Γ_7	$\pi^0\gamma$	(1.31±0.13) $\times 10^{-3}$	
Γ_8	e^+e^-	(2.99±0.08) $\times 10^{-4}$	S=1.2
Γ_9	$\mu^+\mu^-$	(2.5 ±0.4) $\times 10^{-4}$	
Γ_{10}	ηe^+e^-	(1.3 $^{+0.8}_{-0.6}$) $\times 10^{-4}$	
Γ_{11}	$\pi^+\pi^-$	(8 $^{+5}_{-4}$) $\times 10^{-5}$	S=1.5
Γ_{12}	$\omega\gamma$	< 5 %	CL=84%
Γ_{13}	$\rho\gamma$	< 7 $\times 10^{-4}$	CL=90%
Γ_{14}	$\pi^+\pi^-\gamma$	< 3 $\times 10^{-5}$	CL=90%
Γ_{15}	$f_0(980)\gamma$	< 1 $\times 10^{-4}$	CL=90%
Γ_{16}	$\pi^0\pi^0\gamma$	< 1 $\times 10^{-3}$	CL=90%
Γ_{17}	$\pi^+\pi^-\pi^+\pi^-$	< 8.7 $\times 10^{-4}$	CL=90%
Γ_{18}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1.5 $\times 10^{-4}$	CL=95%
Γ_{19}	$\pi^0 e^+e^-$	< 1.2 $\times 10^{-4}$	CL=90%
Γ_{20}	$\pi^0\eta\gamma$	< 2.5 $\times 10^{-3}$	CL=90%
Γ_{21}	$a_0(980)\gamma$	< 5 $\times 10^{-3}$	CL=90%
Γ_{22}	$\eta'(958)\gamma$	(1.2 $^{+0.7}_{-0.5}$) $\times 10^{-4}$	
Γ_{23}	$\mu^+\mu^-\gamma$	(2.3 ±1.0) $\times 10^{-5}$	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 29 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 26.9 for 26 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc}
x_2 & -53 & & \\
x_3 & -60 & -36 & \\
x_6 & -3 & -3 & -2 \\
\hline
 & x_1 & x_2 & x_3
\end{array}$$

ϕ(1020) BRANCHING RATIOS

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.491±0.008 OUR FIT Error includes scale factor of 1.3.				
0.493±0.010 OUR AVERAGE				
0.492±0.012	2913	AKHMETSHIN 95	CMD2	$e^+e^- \to K^+K^-$
0.44 ±0.05	321	KALBFLEISCH 76	HBC	2.18 $K^-p \to \Lambda K^+K^-$
0.49 ±0.06	270	DEGROOT 74	HBC	4.2 $K^-p \to \Lambda\phi$
0.540±0.034	565	BALAKIN 71	OSPK	$e^+e^- \to K^+K^-$
0.48 ±0.04	252	LINDSEY 66	HBC	2.1–2.7 $K^-p \to \Lambda K^+K^-$

$\Gamma(K^0_L K^0_S)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.341±0.006 OUR FIT Error includes scale factor of 1.2.				
0.331±0.009 OUR AVERAGE				
0.335±0.010	40644	AKHMETSHIN 95	CMD2	$e^+e^- \to K^0_L K^0_S$
0.326±0.035		DOLINSKY 91	ND	$e^+e^- \to K^0_L K^0_S$
0.310±0.024		DRUZHININ 84	ND	$e^+e^- \to K^0_L K^0_S$

• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.27 ±0.03	133	KALBFLEISCH	76	HBC	2.18 $K^-p\to\Lambda K_L^0K_S^0$
0.257±0.030	95	BALAKIN	71	OSPK	$e^+e^-\to K_L^0K_S^0$
0.40 ±0.04	167	LINDSEY	66	HBC	2.1–2.7 $K^-p\to\Lambda K_L^0K_S^0$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.155±0.007 OUR FIT	Error includes scale factor of 1.5.				
0.151±0.009 OUR AVERAGE	Error includes scale factor of 1.7.				
0.161±0.008	11761	AKHMETSHIN	95	CMD2	$e^+e^-\to\pi^+\pi^-\pi^0$
0.143±0.007		DOLINSKY	91	ND	$e^+e^-\to\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.139±0.007		[7] PARROUR	76B	OSPK	e^+e^-

[7] Using total width 4.1 MeV. The $\rho\pi$ to 3π mode is more than 80%. at the 90% confidence level.

$\Gamma(K_L^0K_S^0)/\Gamma(K\overline{K})$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.410±0.007 OUR FIT	Error includes scale factor of 1.2.				
0.45 ±0.04 OUR AVERAGE					
0.44 ±0.07		LONDON	66	HBC	2.24 $K^-p\to\Lambda K\overline{K}$
0.48 ±0.07	52	BADIER	65B	HBC	3 K^-p
0.40 ±0.10	34	SCHLEIN	63	HBC	1.95 $K^-p\to\Lambda K\overline{K}$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K\overline{K})$ $\Gamma_3/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.187±0.010 OUR FIT	Error includes scale factor of 1.5.			
0.24 ±0.04 OUR AVERAGE				
0.237±0.039	CERRADA	77B	HBC	4.2 $K^-p\to\Lambda3\pi$
0.30 ±0.15	LONDON	66	HBC	2.24 $K^-p\to\Lambda\pi^+\pi^-\pi^0$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K_L^0K_S^0)$ Γ_3/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.456±0.025 OUR FIT	Error includes scale factor of 1.5.				
0.51 ±0.05 OUR AVERAGE					
0.56 ±0.07	3681	BUKIN	78C	OLYA	$e^+e^-\to K_L^0K_S^0$, $\pi^+\pi^-\pi^0$
0.47 ±0.06	516	COSME	74	OSPK	$e^+e^-\to\pi^+\pi^-\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ Γ_9/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
2.5 ±0.4 OUR AVERAGE				
2.69±0.46	[8] HAYES	71	CNTR	8.3,9.8 $\gamma C\to\mu^+\mu^-X$
2.17±0.60	[8] EARLES	70	CNTR	6.0 $\gamma C\to\mu^+\mu^-X$

[8] Neglecting interference between resonance and continuum.

$\Gamma(\eta\gamma)/\Gamma_{\rm total}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0126±0.0006 OUR FIT	Error includes scale factor of 1.1.				
0.0126±0.0005 OUR AVERAGE	Error includes scale factor of 1.1.				
0.0118±0.0011	279	[9] AKHMETSHIN	95	CMD2	$e^+e^-\to\pi^+\pi^-3\gamma$
0.0130±0.0006		[10] DRUZHININ	84	ND	$e^+e^-\to3\gamma$
0.014 ±0.002		[11] DRUZHININ	84	ND	$e^+e^-\to6\gamma$
0.0088±0.0020	290	KURDADZE	83C	OLYA	$e^+e^-\to3\gamma$
0.0135±0.0029		ANDREWS	77	CNTR	6.7–10 γCu
0.015 ±0.004	54	[10] COSME	76	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0121±0.0007		[12] BENAYOUN	96	RVUE	0.54-1.04 $e^+e^-\to\eta\gamma$

[9] From $\pi^+\pi^-\pi^0$ decay mode of η.
[10] From 2γ decay mode of η.
[11] From $3\pi^0$ decay mode of η.
[12] Reanalysis of DRUZHININ 84, DOLINSKY 89, and DOLINSKY 91 taking into account a triangle anomaly contribution.

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 0.3	90	[13] AKHMETSHIN	97C	CMD2	$e^+e^-\to\pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<600	90	KALBFLEISCH	75	HBC	2.18 $K^-p\to\Lambda\pi^+\pi^-\gamma$
< 70	90	COSME	74	OSPK	$e^+e^-\to\pi^+\pi^-\gamma$
<400	90	LINDSEY	65	HBC	2.1–2.7 $K^-p\to\Lambda\pi^+\pi^-$ neutrals

[13] For $E_\gamma > 20$ MeV and assuming that $B(\phi(1020)\to f_0(980)\gamma)$ is negligible.

$\Gamma(\omega\gamma)/\Gamma_{\rm total}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.05	84	LINDSEY	66	HBC	2.1–2.7 $K^-p\to\Lambda\pi^+\pi^-$ neutrals

$\Gamma(\rho\gamma)/\Gamma_{\rm total}$ Γ_{13}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 7	90	AKHMETSHIN	97C	CMD2	$e^+e^-\to\pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<200	84	LINDSEY	66	HBC	2.1–2.7 $K^-p\to\Lambda\pi^+\pi^-$ neutrals

$\Gamma(e^+e^-)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.99±0.08 OUR AVERAGE	Error includes scale factor of 1.2.				
2.88±0.09	55600	AKHMETSHIN	95	CMD2	$e^+e^-\to$ hadrons
3.00±0.21	3681	BUKIN	78C	OLYA	$e^+e^-\to$ hadrons
3.10±0.14		[14] PARROUR	76	OSPK	e^+e^-
3.3 ±0.3		COSME	74	OSPK	$e^+e^-\to$ hadrons
2.81±0.25	681	BALAKIN	71	OSPK	$e^+e^-\to$ hadrons
3.50±0.27		CHATELUS	71	OSPK	e^+e^-

[14] Using total width 4.2 MeV. They detect 3π mode and observe significant interference with ω tail. This is accounted for in the result quoted above.

$\Gamma(\pi^0\gamma)/\Gamma_{\rm total}$ Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.31±0.13 OUR AVERAGE					
1.30±0.13		DRUZHININ	84	ND	$e^+e^-\to3\gamma$
1.4 ±0.5	32	COSME	76	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.26±0.17		[12] BENAYOUN	96	RVUE	0.54-1.04 $e^+e^-\to\pi^0\gamma$

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
$0.8^{+0.5}_{-0.4}$ OUR AVERAGE	Error includes scale factor of 1.5.				
$0.63^{+0.37}_{-0.28}$		[15] GOLUBEV	86	ND	$e^+e^-\to\pi^+\pi^-$
$1.94^{+1.03}_{-0.81}$		[15] VASSERMAN	81	OLYA	e^+e^-
<6.6	95	BUKIN	78B	OLYA	$e^+e^-\to\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.7	95	ALVENSLEB...	72	CNTR	6.7 $\gamma C\to C\pi^+\pi^-$

[15] Using $\Gamma(e^+e^-)/\Gamma_{\rm total} = 3.1\times10^{-4}$.

$\Gamma(K_L^0K_S^0)/\Gamma(K^+K^-)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.695±0.021 OUR FIT	Error includes scale factor of 1.2.				
0.740±0.031 OUR AVERAGE					
0.70 ±0.06	2732	BUKIN	78C	OLYA	$e^+e^-\to K_L^0K_S^0$
0.82 ±0.08		LOSTY	78	HBC	4.2 $K^-p\to\phi$hyperon
0.71 ±0.05		LAVEN	77	HBC	10 $K^-p\to K^+K^-\Lambda$
0.71 ±0.08		LYONS	77	HBC	3–4 $K^-p\to\Lambda\phi$
0.89 ±0.10	144	AGUILAR-...	72B	HBC	3.9,4.6 K^-p

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^+K^-)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.317±0.017 OUR FIT	Error includes scale factor of 1.5.				
0.28 ±0.09	34	AGUILAR-...	72B	HBC	3.9,4.6 K^-p

$\Gamma(\eta e^+e^-)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$1.3^{+0.8}_{-0.6}$	7	GOLUBEV	85	ND	$e^+e^-\to\gamma\gamma e^+e^-$

$\Gamma(\eta'(958)\gamma)/\Gamma_{\rm total}$ Γ_{22}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$1.2^{+0.7}_{-0.5}\pm0.2$		6	[16] AKHMETSHIN	97B	CMD2	$e^+e^-\to\pi^+\pi^-3\gamma$
<4.1	90		DRUZHININ	87	ND	$e^+e^-\to\gamma\eta\pi^+\pi^-$

[16] Using the value $B(\phi\to\eta\gamma) = (1.26\pm0.06)\times10^{-2}$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{\rm total}$ Γ_{16}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1	90	DRUZHININ	87	ND	$e^+e^-\to5\gamma$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_{18}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	95	BARKOV	88	CMD	$e^+e^-\to\pi^+\pi^-\pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{17}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<8.7	90	CORDIER	79	WIRE	$e^+e^-\to4\pi$

$\Gamma(f_0(980)\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
< 1	90	[17] AKHMETSHIN 97C	CMD2	$e^+e^- \rightarrow \pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 7	90	[18] AKHMETSHIN 97C	CMD2	$e^+e^- \rightarrow \pi^+\pi^-\gamma$
<20	90	DRUZHININ 87	ND	$e^+e^- \rightarrow \pi^0\pi^0\gamma$

[17] For destructive interference with the Bremsstrahlung process

[18] For constructive interference with the Bremsstrahlung process

$\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	DOLINSKY 88	ND	$e^+e^- \rightarrow \pi^0 e^+ e^-$

$\Gamma(\pi^0 \eta\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<2.5	90	DOLINSKY 91	ND	$e^+e^- \rightarrow \pi^0\eta\gamma$

$\Gamma(a_0(980)\gamma)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<5	90	DOLINSKY 91	ND	$e^+e^- \rightarrow \pi^0\eta\gamma$

$\Gamma(\eta'(958)\gamma)/\Gamma(\eta\gamma)$ — Γ_{22}/Γ_6

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
$9.5^{+5.2}_{-4.0}\pm1.4$	6	AKHMETSHIN 97B	CMD2	$e^+e^- \rightarrow \pi^+\pi^- 3\gamma$

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID	TECN	COMMENT
2.3±1.0	824±33	[19] AKHMETSHIN 97C	CMD2	$e^+e^- \rightarrow \mu^+\mu^-\gamma$

[19] For E_γ > 20 MeV.

$\phi(1020)$ REFERENCES

AKHMETSHIN	97B	PL B415 445	R.R. Akhmetshin, Anashkin+	(NOVO, BOST, PITT, YALE)
AKHMETSHIN	97C	PL B415 452	+Aksenov+	(NOVO, BOST, PITT, YALE)
BENAYOUN	96	ZPHY C72 221	M. Benayoun+	(IPNP, NOVO)
AKHMETSHIN	95	PL B364 199	+Akesnov+	(NOVO, BOST, PITT, MINN, YALE)
DOLINSKY	91	PRPL 202 99	+Druzhinin, Dubrovin+	(NOVO)
DOLINSKY	89	ZPHY C42 511	+Druzhinin, Dubrovin, Golubev+	(NOVO)
BARKOV	88	SJNP 47 248	+Vasserman, Vorobyev, Ivanov+	(NOVO)
		Translated from YAF 47 393.		
DOLINSKY	88	SJNP 48 277	+Druzhinin, Dubrovin, Golubev+	(NOVO)
		Translated from YAF 48 442.		
DRUZHININ	87	ZPHY C37 1	+Dubrovin, Eidelman, Golubev+	(NOVO)
ARMSTRONG	86	PL 166B 245	+Bloodworth, Carney+	(ATHU, BARI, BIRM, CERN)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BEBEK	86	PRL 56 1893	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
DAVENPORT	86	PR 33 2519		(TUFTS, ARIZ, FNAL, FSU, NDAM, VAND)
DIJKSTRA	86	ZPHY C31 375	+Bailey+	(ANIK, BRIS, CERN, CRAC, MPIM, RAL)
FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
GOLUBEV	86	SJNP 44 409	+Druzhinin, Ivanchenko, Perevedentsev+	(NOVO)
		Translated from YAF 44 633.		
ALBRECHT	85D	PL 153B 343	+Drescher, Binder, Drews+	(ARGUS Collab.)
GOLUBEV	85	SJNP 41 756	+Druzhinin, Ivanchenko, Peryshkin+	(NOVO)
		Translated from YAF 41 1183.		
DRUZHININ	84	PL 144B 136	+Golubev, Ivanchenko, Peryshkin+	(NOVO)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, CURIN+)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
KURDADZE	83C	JETPL 38 366	+Lelchuk, Root+	(NOVO)
		Translated from ZETFP 38 306.		
ARENTON	82	PR D25 2241	+Ayres, Diebold, May, Swallow+	(ANL, ILL)
PELLINEN	82	PS 25 599	+Roos	(HELS)
DAUM	81	PL 100B 439	+Bardsley+	(AMST, BRIS, CERN, CRAC, MPIM+)
IVANOV	81	PL 107B 297	+Kurdadze, Lelchuk, Sidorov, Skrinsky+	(NOVO)
Also	82	Private Comm.	Eidelman	(NOVO)
VASSERMAN	81	PL 99B 62	+Kurdadze, Sidorov, Skrinsky+	(NOVO)
CORDIER	80	NP B172 13	+Delcourt, Eschstruth, Fulda+	(LALO)
CORDIER	79	PL 81B 389	+Delcourt, Eschstruth, Fulda+	(LALO)
BUKIN	78B	SJNP 27 521	+Kurdadze, Sidorov, Skrinsky+	(NOVO)
		Translated from YAF 27 985.		
BUKIN	78C	SJNP 27 516	+Kurdadze, Serednyakov, Sidorov+	(NOVO)
		Translated from YAF 27 976.		
COOPER	78B	NP B146 1	+Ganguli+	(TATA, CERN, CDEF, MADR)
LOSTY	78	NP B133 38	+Holmgren, Blokzijl+	(CERN, AMST, NIJM, OXF)
AKERLOF	77	PRL 39 861	+Alley, Bintinger, Ditzler+	(FNAL, MICH, PURD)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
BALDI	77	PL 68B 381	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA)
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF)
COHEN	77	PRL 38 269	+Ayres, Diebold, Kramer, Pawlicki, Wicklund	(ANL)
LAVEN	77	NP B127 43	+Otter, Klein+	(AACH3, BERL, CERN, LOIC, WIEN)
LYONS	77	NP B125 207	+Cooper, Clark	(OXF)
COSME	76	PL 63B 352	+Courau, Dudelzak, Grelaud, Jean-Marie+	(ORSAY)
KALBFLEISCH	76	PR D13 22	+Strand, Chapman	(BNL, MICH)
PARROUR	76	PL 63B 357	+Grelaud, Cosme, Courau, Dudelzak+	(ORSAY)
PARROUR	76B	PL 63B 362	+Grelaud, Cosme, Courau, Dudelzak+	(ORSAY)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
AYRES	74	PRL 32 1463	+Diebold, Greene, Kramer, Levine+	(ANL)
BESCH	74	NP B70 257	+Hartmann, Kose, Krautschneider, Paul+	(BONN)
COSME	74	PL 48B 155	+Jean-Marie, Jullian, Laplanche+	(ORSAY)
COSME	74B	PL 48B 159	+Jean-Marie, Jullian, Laplanche+	(ORSAY)
DEGROOT	74	NP B74 77	+Hoogland, Jongejans, Metzger+	(AMST, NIJM)
BALLAM	73	PR D7 3150	+Chadwick, Eisenberg, Bingham+	(SLAC, LBL)
BINNIE	73B	PR D8 2789	+Carr, Debenham, Duane+	(LOIC, SHMP)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
ALVENSLEB...	72	PRL 28 66	Alvensleben, Becker, Biggs, Binkley+	(MIT, DESY)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH)
COLLEY	72	NP B50 1	+Jobes, Riddiford, Griffiths+	(BIRM, GLAS)
BALAKIN	71	PL 34B 328	+Budker, Pakhtusova, Sidorov, Skrinsky+	(NOVO)
CHATELUS	71	Thesis LAL 1247		(STRB)
Also	70	PL 32 416	Bizot, Buon, Chatelus, Jeanjean+	(ORSAY)
HAYES	71	PR D4 899	+Imlay, Joseph, Keizer, Stein	(CORN)
STOTTLE...	71	Thesis ORO 2504 170	Stottlemyer	(UMD)
BIZOT	70	PL 32 416	+Buon, Chatelus, Jeanjean+	(ORSAY)
Also	69	Liverpool Sym. 69	Perez-y-Jorba	
EARLES	70	PRL 25 1312	+Faissler, Gettner, Lutz, Moy, Tang+	(NEAS)
LINDSEY	66	PR 147 913	+Smith	(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IGJPC
BADIER	65B	PL 17 337	+Demoulin, Barloutaud+	(EPOL, SACL, AMST)
LINDSEY	65	PRL 15 221	+Smith	(LRL)
LINDSEY 65 data included in LINDSEY 66.				
SCHLEIN	63	PRL 10 368	+Slater, Smith, Stork, Ticho	(UCLA) IGJP

OTHER RELATED PAPERS

ACHASOV	97C	PR D56 4084	N.N. Achasov+	
ACHASOV	97D	PR D56 203	N.N. Achasov+	
ACHASOV	95	PLB 363 106	+Gubin	(NOVM)
KAMAL	92	PL B284 421	+Xu	(ALBE)
GEORGIO...	85	PL 152B 428	Georgiopoulos+	(TUFTS, ARIZ, FNAL, FSU, NDAM+)
GELFAND	63B	PRL 11 438	+Miller, Nussbaum, Kirsch+	(COLU, RUTG)
BERTANZA	62	PRL 9 180	+Brisson, Connolly, Hart+	(BNL, SYRA)

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

$h_1(1170)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1170±20 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1168± 4	ANDO 92	SPEC		$8\ \pi^- p \rightarrow \pi^+\pi^-\pi^0 n$
1166± 5±3	[1] ANDO 92	SPEC		$8\ \pi^- p \rightarrow \pi^+\pi^-\pi^0 n$
1190±60	[2] DANKOWY... 81	SPEC	0	$8\ \pi p \rightarrow 3\pi n$

[1] Average and spread of values using 2 variants of the model of BOWLER 75.

[2] Uses the model of BOWLER 75.

$h_1(1170)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
360±40 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
345± 6	ANDO 92	SPEC		$8\ \pi^- p \rightarrow \pi^+\pi^-\pi^0 n$
375± 6±34	[3] ANDO 92	SPEC		$8\ \pi^- p \rightarrow \pi^+\pi^-\pi^0 n$
320±50	[4] DANKOWY... 81	SPEC	0	$8\ \pi p \rightarrow 3\pi n$

[3] Average and spread of values using 2 variants of the model of BOWLER 75.

[4] Uses the model of BOWLER 75.

$h_1(1170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen

$h_1(1170)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	ANDO 92	SPEC	$8\ \pi^- p \rightarrow \pi^+\pi^-\pi^0 n$
seen	ATKINSON 84	OMEG	20–70 $\gamma p \rightarrow \pi^+\pi^-\pi^0 p$
seen	DANKOWY... 81	SPEC	$8\ \pi p \rightarrow 3\pi n$

$h_1(1170)$ REFERENCES

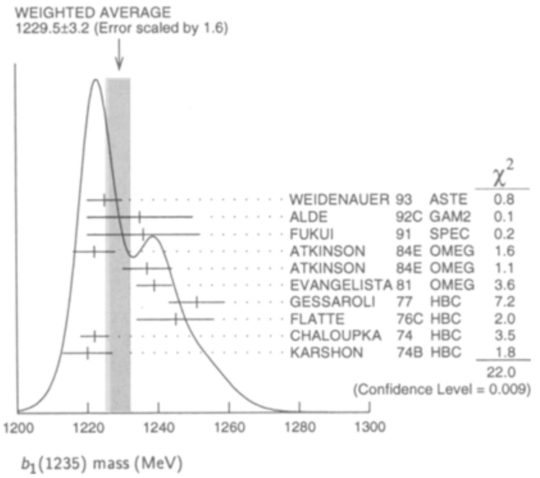
ANDO	92	PL B291 496	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, AKIT)
ATKINSON	84	NP B231 15	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
DANKOWY...	81	PRL 46 580	Dankowych+	(TNTO, BNL, CARL, MCGI, OHIO)
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXFTP, DARE)

$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

$b_1(1235)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1229.5± 3.2 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.					
1225 ± 5		WEIDENAUER	93	ASTE		$\overline{p}p \rightarrow 2\pi^+2\pi^-\pi^0$
1235 ±15		ALDE	92C	GAM2		38,100 $\pi^- p \rightarrow \omega\pi^0 n$
1236 ±16		FUKUI	91	SPEC		8.95 $\pi^- p \rightarrow \omega\pi^0 n$
1222 ± 6		ATKINSON	84E	OMEG	±	25–55 $\gamma p \rightarrow \omega\pi X$
1237 ± 7		ATKINSON	84E	OMEG	0	25–55 $\gamma p \rightarrow \omega\pi X$
1239 ± 5		EVANGELISTA	81	OMEG	−	12 $\pi^- p \rightarrow \omega\pi p$
1251 ± 8	450	GESSAROLI	77	HBC	−	11 $\pi^- p \rightarrow \pi^-\omega p$
1245 ±11	890	FLATTE	76C	HBC	−	4.2 $K^- p \rightarrow \pi^-\omega\Sigma^+$
1222 ± 4	1400	CHALOUPKA	74	HBC	−	3.9 $\pi^- p$
1220 ± 7	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1190 ±10		AUGUSTIN	89	DM2	±	$e^+e^- \rightarrow 5\pi$
1213 ± 5		ATKINSON	84C	OMEG	0	20–70 γp
1271 ±11		COLLICK	84	SPEC	+	200 $\pi^+ Z \rightarrow Z\pi\omega$



$b_1(1235)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
142± 9 OUR AVERAGE	Error includes scale factor of 1.2.					
113±12		WEIDENAUER	93	ASTE		$\overline{p}p \rightarrow 2\pi^+2\pi^-\pi^0$
160±30		ALDE	92C	GAM2		38,100 $\pi^- p \rightarrow \omega\pi^0 n$
151±31		FUKUI	91	SPEC		8.95 $\pi^- p \rightarrow \omega\pi^0 n$
170±15		EVANGELISTA	81	OMEG	−	12 $\pi^- p \rightarrow \omega\pi p$
170±50	225	BALTAY	78B	HBC	+	15 $\pi^+ p \rightarrow p4\pi$
155±32	450	GESSAROLI	77	HBC	−	11 $\pi^- p \rightarrow \pi^-\omega p$
182±45	890	FLATTE	76C	HBC	−	4.2 $K^- p \rightarrow \pi^-\omega\Sigma^+$
135±20	1400	CHALOUPKA	74	HBC	−	3.9 $\pi^- p$
156±22	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
210±19		AUGUSTIN	89	DM2	±	$e^+e^- \rightarrow 5\pi$
231±14		ATKINSON	84C	OMEG	0	20–70 γp
232±29		COLLICK	84	SPEC	+	200 $\pi^+ Z \rightarrow Z\pi\omega$

$b_1(1235)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\omega\pi$ [D/S amplitude ratio = 0.29 ± 0.04]	dominant	
Γ_2	$\pi^\pm\gamma$	$(1.6\pm0.4)\times10^{-3}$	
Γ_3	$\eta\rho$	seen	
Γ_4	$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%
Γ_5	$(K\overline{K})^\pm\pi^0$	< 8 %	90%
Γ_6	$K^0_S K^0_L \pi^\pm$	< 6 %	90%
Γ_7	$K^0_S K^0_S \pi^\pm$	< 2 %	90%
Γ_8	$\phi\pi$	< 1.5 %	84%

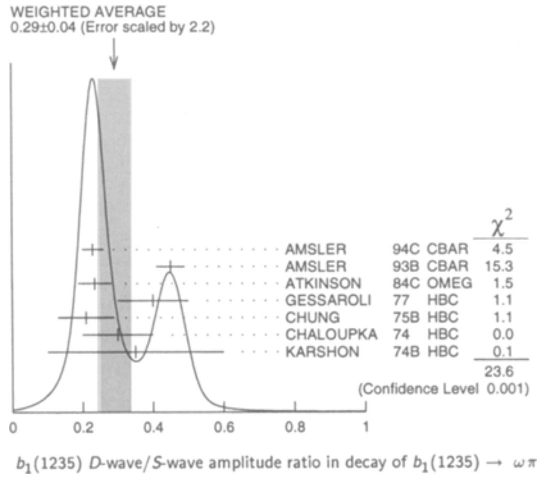
$b_1(1235)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ Γ_2

VALUE (keV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
230±60	COLLICK	84	SPEC	+	200 $\pi^+ Z \rightarrow Z\pi\omega$

$b_1(1235)$ *D*-wave/*S*-wave AMPLITUDE RATIO IN DECAY OF $b_1(1235) \rightarrow \omega\pi$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.29 ±0.04 OUR AVERAGE	Error includes scale factor of 2.2. See the ideogram below.					
0.23 ±0.03		AMSLER	94C	CBAR		0.0 $\overline{p}p \rightarrow \omega\eta\pi^0$
0.45 ±0.04		AMSLER	93B	CBAR		0.0 $\overline{p}p \rightarrow \omega\pi^0\pi^0$
0.235±0.047		ATKINSON	84C	OMEG		20–70 γp
$0.4\ ^{+0.1}_{-0.1}$		GESSAROLI	77	HBC	−	11 $\pi^- p \rightarrow \pi^-\omega p$
0.21 ±0.08		CHUNG	75B	HBC	+	7.1 $\pi^+ p$
0.3 ±0.1		CHALOUPKA	74	HBC	−	3.9–7.5 $\pi^- p$
0.35 ±0.25	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$



$b_1(1235)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ Γ_3/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.10	ATKINSON	84D	OMEG	20–70 γp

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\omega\pi)$ Γ_4/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.5	ABOLINS	63	HBC	+	3.5 $\pi^+ p$

$\Gamma((K\overline{K})^\pm\pi^0)/\Gamma(\omega\pi)$ Γ_5/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.08	90	BALTAY	67	HBC	±	0.0 $\overline{p}p$

$\Gamma(K^0_S K^0_L \pi^\pm)/\Gamma(\omega\pi)$ Γ_6/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.06	90	BALTAY	67	HBC	±	0.0 $\overline{p}p$

$\Gamma(K^0_S K^0_S \pi^\pm)/\Gamma(\omega\pi)$ Γ_7/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.02	90	BALTAY	67	HBC	±	0.0 $\overline{p}p$

$\Gamma(\phi\pi)/\Gamma(\omega\pi)$ **Γ_8/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.004	95	VIKTOROV	96	SPEC	0	32.5 $\pi^- p \to K^+ K^- \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.04	95	BIZZARRI	69	HBC	±	0.0 $\overline{p} p$
<0.015		DAHL	67	HBC		1.6–4.2 $\pi^- p$

$b_1(1235)$ REFERENCES

VIKTOROV 96 PAN 59 1184 +Golovkin+ (SERP)
Translated from YAF 59 1239.
AMSLER 94C PL B327 425 +Armstrong, Ravndal+ (Crystal Barrel Collab.)
AMSLER 93B PL B311 362 +Armstrong, v.Dombrowski+ (Crystal Barrel Collab.)
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
ALDE 92C ZPHY C54 553 +Bencheikh, Binon+ (BELG, SERP, KEK, LANL, LAPP)
FUKUI 91 PL B257 241 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
ATKINSON 84D NP B242 269 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 84E PL 138B 459 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
COLLICK 84 PRL 53 2374 +Heppelmann, Berg+ (MINN, ROCH, FNAL)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI) JP
FLATTE 76C PL 64B 225 +Gay, Blokzijl, Metzger+ (CERN, AMST, NIJM, OXF) JP
CHUNG 75B PR D11 2426 +Protopopescu, Lynch, Flatte+ (BNL, LBL, UCSC) JP
CHALOUPKA 74 PL 51B 407 +Ferrando, Losty, Montanet (CERN) JP
KARSHON 74B PR D10 3608 +Mikenberg, Eisenberg, Pitluck, Ronat+ (REHO) JP
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
BALTAY 67 PRL 18 93 +Franzini, Severiens, Yeh, Zanello (COLU)
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL)
ABOLINS 63 PRL 11 381 +Lander, Mehlhop, Nguyen, Yager (UCSD)

OTHER RELATED PAPERS

GOLOVKIN 97 ZPHY A359 4335 S.V. Golovkin, Kozhevnikov+ (SERP, ITEP)
BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
GOLDHABER 65 PRL 15 118 +Goldhaber, Kadyk, Shen (LRL)
CARMONY 64 PRL 12 254 +Lander, Rindfleisch, Xuong, Yager (UCB) JP
BONDAR 63B PL 5 209 +Dodd+ (AACH, BIRM, HAMB, LOIC, MPIM)

$a_1(1260)$

$I^G(J^{PC}) = 1^-(1^{++})$

THE $a_1(1260)$

Written March 1998 by S. Eidelman (Novosibirsk).

The main experimental data on the $a_1(1260)$ may be grouped into two classes:

(1) ***Hadronic Production.*** This comprises diffractive production with incident π^- (DAUM 80, 81B) and charge-exchange production with low-energy π^- (DANKOWYCH 81, ANDO 92). The 1980's experiments explain the $I^G L J^P = 1^+ S 0^+$ data using a phenomenological amplitude consisting of a rescattered Deck amplitude plus a direct resonance-production term. They agree on an $a_1(1260)$ mass of about 1270 MeV and a width of 300–380 MeV. ANDO 92 finds rather lower values for the mass (1121 MeV) and width (239 MeV) in a partial-wave analysis based on the isobar model of the $\pi^+\pi^-\pi^0$ system. However, in this analysis, only Breit-Wigner terms were considered.

(2) ***τ decay.*** Five experiments reported good data on $\tau \to a_1(1260)\nu_\tau \to \rho\pi\nu_\tau$ (RUCKSTUHL 86, SCHMIDKE 86, ALBRECHT 86B, BAND 87, and ACKERSTAFF 97R). They are somewhat inconsistent concerning the $a_1(1260)$ mass, which can, however, be attributed to model-dependent systematic uncertainties (BOWLER 86, ALBRECHT 93C, ACKERSTAFF 97R). They all find a width greater than 400 MeV.

The discrepancies between the hadronic- and τ-decay results have stimulated several reanalyses. BASDEVANT 77, 78 used the early diffractive dissociation and τ decay data and showed that they could be well reproduced with an a_1 resonance mass of 1180 ± 50 MeV and width of 400 ± 50 MeV. Later, BOWLER 86, TORNQVIST 87, ISGUR 89, and IVANOV 91 have studied the process $\tau \to 3\pi\nu_\tau$. Despite quite different approaches, they all found a good overall description of the τ-decay data with an $a_1(1260)$ mass near 1230 MeV, consistent with the hadronic data. However, their widths remain significantly larger (400–600 MeV) than those extracted from diffractive-hadronic data. This is also the case with the later OPAL experiment (ACKERSTAFF 97R). In the high statistics analysis of ACKERSTAFF 97R the models of ISGUR 89 and KUHN 90 are used to fit distributions of the 3π invariant mass as well as the 2π invariant mass projections of the Dalitz plot and neither model is found to provide a completely satisfactory description of the data. Another recent high statistics analysis of ABREU 98G obtains good description of the $\tau \to 3\pi$ data using the model of FEINDT 90 which includes the a_1' meson, a radial excitation of the $a_1(1260)$ meson, with a mass of 1700 MeV and a width of 300 MeV.

BOWLER 88 showed that good fits to both the hadronic and the τ-decay data could be obtained with a width of about 400 MeV. However, applying the same type of analysis to the ANDO 92 data, the low mass and narrow width they obtained with the Breit-Wigner PWA do not change appreciably.

CONDO 93 found no evidence for charge-exchange photoproduction of the $a_1(1260)$ (but found a clear signal of $a_2(1320)$ photoproduction). They show that it is consistent with either an extremely large $a_1(1260)$ hadronic width or with a small radiative width to $\pi\gamma$, which could be accommodated if the a_1 mass is somewhat below 1260 MeV.

$a_1(1260)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1230±40 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1262± 9± 7	[1,2] ACKERSTAFF	97R	OPAL		E^{ee}_{cm}= 88–94, $\tau \to 3\pi\nu$
1210± 7± 2	[2,3] ACKERSTAFF	97R	OPAL		E^{ee}_{cm}= 88–94, $\tau \to 3\pi\nu$
1211± 7	ALBRECHT	93C	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1121± 8	[4] ANDO	92	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
1242±37	[5] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1260±14	[6] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1250± 9	[7] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1208±15	ARMSTRONG	90	OMEG	0	300.0$pp \to pp\pi^+\pi^-\pi^0$
1220±15	[8] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1260±25	[9] BOWLER	88	RVUE		
1166±18±11	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1164±41±23	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
1250±40	[8] TORNQVIST	87	RVUE		
1046±11	ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1056±20±15	RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1194±14±10	SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1240±80	[10] DANKOWY...	81	SPEC	0	8.45 $\pi^- p \to n3\pi$
1280±30	[10] DAUM	81B	CNTR		63,94 $\pi^- p \to p3\pi$
1041±13	[11] GAVILLET	77	HBC	+	4.2 $K^- p \to \Sigma 3\pi$

[1] Uses the model of KUHN 90.
[2] Supersedes AKERS 95P
[3] Uses the model of ISGUR 89.
[4] Average and spread of values using 2 variants of the model of BOWLER 75.
[5] Reanalysis of RUCKSTUHL 86.
[6] Reanalysis of SCHMIDKE 86.
[7] Reanalysis of ALBRECHT 86B.
[8] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[9] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[10] Uses the model of BOWLER 75.
[11] Produced in K^- backward scattering.

$a_1(1260)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
250 to 600 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
621± 32±58	[12,13] ACKERSTAFF	97R	OPAL		E^{ee}_{cm}= 88–94, $\tau \to 3\pi\nu$
457± 15±17	[13,14] ACKERSTAFF	97R	OPAL		E^{ee}_{cm}= 88–94, $\tau \to 3\pi\nu$
446± 21	ALBRECHT	93C	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
239± 11	ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
266± 13± 4	[15] ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
465^{+228}_{-143}	[16] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
298^{+40}_{-34}	[17] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
488± 32	[18] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
430± 50	ARMSTRONG	90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
420± 40	[19] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
396± 43	[20] BOWLER	88	RVUE		
405± 75±25	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
419±108±57	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
521± 27	ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$476^{+132}_{-120}\pm54$	RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
462± 56±30	SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
380±100	[21] DANKOWY...	81	SPEC	0	$8.45\ \pi^- p \to n3\pi$
300± 50	[21] DAUM	81B	CNTR		$63,94\ \pi^- p \to p3\pi$
230± 50	[22] GAVILLET	77	HBC	+	$4.2\ K^- p \to \Sigma 3\pi$

[12] Uses the model of KUHN 90.
[13] Supersedes AKERS 95P
[14] Uses the model of ISGUR 89.
[15] Average and spread of values using 2 variants of the model of BOWLER 75.
[16] Reanalysis of RUCKSTUHL 86.
[17] Reanalysis of SCHMIDKE 86.
[18] Reanalysis of ALBRECHT 86B.
[19] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[20] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[21] Uses the model of BOWLER 75.
[22] Produced in K^- backward scattering.

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$ [D/S amplitude ratio = -0.100 ± 0.028]	dominant
Γ_2	$\pi\gamma$	seen
Γ_3	$\pi(\pi\pi)_{S\text{-wave}}$	possibly seen

$a_1(1260)$ PARTIAL WIDTHS

$\Gamma(\pi\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
640±246	ZIELINSKI	84C	SPEC	$200\ \pi^+ Z \to Z3\pi$

D-wave/S-wave AMPLITUDE RATIO IN DECAY OF $a_1(1260) \to \rho\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.10 ±0.02 ±0.02	[23,24] ACKERSTAFF	97R	OPAL	E^{ee}_{cm}= 88–94, $\tau \to 3\pi\nu$

[23] Uses the model of ISGUR 89.
[24] Supersedes AKERS 95P

$a_1(1260)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.003±0.003	[25] LONGACRE	82	RVUE

[25] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from GAVILLET 77, DAUM 80, and DANKOWYCH 81.

$a_1(1260)$ REFERENCES

ACKERSTAFF	97R	ZPHY C75 593	K. Ackerstaff+	(OPAL Collab.)
AKERS	95P	ZPHY C67 45	+Alexander, Allison, Ametewee+	(OPAL Collab.)
ALBRECHT	93C	ZPHY C58 61	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ANDO	92	PL B291 496	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, AKIT)
IVANOV	91	ZPHY C49 563	+Osipov, Volkov	(JINR)
ARMSTRONG	90	ZPHY C48 213	+Benayoun, Beusch	(WA76 Collab.)
KUHN	90	ZPHY C48 445	J.H. Kuhn, Santamaria+	(MPIM)
ISGUR	89	PR D39 1357	+Morningstar, Reader	(TNTO)
BOWLER	88	PL B209 99		(OXF)
BAND	87	PL B198 297	+Camporesi, Chadwick, Delfino+	(MAC Collab.)
TORNQVIST	87	ZPHY C36 695		(HELS)
ALBRECHT	86B	ZPHY C33 7	+Donker, Gabriel, Edwards+	(ARGUS Collab.)
RUCKSTUHL	86	PRL 56 2132	+Stroynowski, Atwood, Barish+	(DELCO Collab.)
SCHMIDKE	86	PRL 57 527	+Abrams, Matteuzzi, Amidei+	(Mark II Collab.)
ZIELINSKI	84C	PRL 52 1195	+Berg, Chandlee, Cihangir+	(ROCH, MINN, FNAL)
LONGACRE	82	PR D26 83		(BNL)
DANKOWY...	81	PRL 46 580	Dankowych+	(TNTO, BNL, CARL, MCGI, OHIO)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
DAUM	80	PL 89B 281	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
GAVILLET	77	PL 69B 119	+Blockzijl, Engelen+	(AMST, CERN, NIJM, OXF) JP
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXFTP, DARE)

OTHER RELATED PAPERS

ABREU CERN-EP/98-14	98G	PL B (to be publ.)	P. Abreu+	(DELPHI Collab.)
BOLONKIN	95	PAN 58 1535 Translated from YAF 58 1628.	+Vladimirskii, Erofeeva+	(ITEP)
WINGATE	95	PRL 74 4596	+De Grand	(COLO, FSU)
CONDO	93	PR D48 3045	+Handler, Bugg+	(SLAC Hybrid Collab.)
FEINDT	90	ZPHY C48 681	M. Feindt	(HAMB)
IIZUKA	89	PR D39 3357	+Koibuchi, Masuda	(NAGO, IBAR, TSUK)
TORNQVIST	87	ZPHY C36 695		(HELS)
BOWLER	86	PL B182 400		(OXF)
BASDEVANT	78	PRL 40 994	+Berger	(FNAL, ANL) JP
BASDEVANT	77	PR D16 657	+Berger	(FNAL, ANL) JP
ADERHOLZ	64	PL 10 226	+	(AACH3, BERL, BIRM, BONN, DESY, HAMB+)
GOLDHABER	64	PRL 12 336	+Brown, Kadyk, Shen+	(LRL, UCB)
LANDER	64	PRL 13 346A	+Abolins, Carmony, Hendricks, Xuong+	(UCSD) JP
BELLINI	63	NC 29 896	+Fiorini, Herz, Negri, Ratti	(MILA)

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

$f_2(1270)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1275.0± 1.2 OUR AVERAGE					
1278 ± 5		[1] BERTIN	97C	OBLX	$0.0\ \overline{p}p \to \pi^+\pi^-\pi^0$
1272 ± 8	200k	PROKOSHKIN	94	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
1269.7± 5.2	5730	AUGUSTIN	89	DM2	$e^+e^- \to 5\pi$
1283 ± 8	400	[2] ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1274 ± 5		[2] AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1283 ± 6		[3] LONGACRE	86	MPS	$22\ \pi^- p \to n2K^0_S$
1276 ± 7		COURAU	84	DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
1273.3± 2.3		[4] CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
1280 ± 4		[5] CASON	82	STRC	$8\ \pi^+ p \to \Delta^{++}\pi^0\pi^0$
1281 ± 7	11600	GIDAL	81	MRK2	J/ψ decay
1282 ± 5		[6] CORDEN	79	OMEG	$12–15\ \pi^- p \to n2\pi$
1269 ± 4	10k	APEL	75	NICE	$40\ \pi^- p \to n2\pi^0$
1272 ± 4	4600	ENGLER	74	DBC	$6\ \pi^+ n \to \pi^+\pi^- p$
1277 ± 4	5300	FLATTE	71	HBC	$7.0\ \pi^+ p$
1273 ± 8		[2] STUNTEBECK	70	HBC	$8\ \pi^- p$, $5.4\ \pi^+ d$
1265 ± 8		BOESEBECK	68	HBC	$8\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1260 ±10		[7] ALDE	97	GAM2	$450\ pp \to pp\pi^0\pi^0$
1278 ± 6		[7] GRYGOREV	96	SPEC	$40\ \pi^- N \to K^0_S K^0_S X$
1262 ±11		AGUILAR-...	91	EHS	$400\ pp$
1275 ±10		AKER	91	CBAR	$0.0\ \overline{p}p \to 3\pi^0$
1220 ±10		BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
1288 ±12		ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^- X$
1284 ±30	3k	BINON	83	GAM2	$38\ \pi^- p \to n2\eta$
1280 ±20	3k	APEL	82	CNTR	$25\ \pi^- p \to n2\pi^0$
1284 ±10	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
1258 ±10	600	TAKAHASHI	72	HBC	$8\ \pi^- p \to n2\pi$
1275 ±13		ARMENISE	70	HBC	$9\ \pi^+ n \to p\pi^+\pi^-$
1261 ± 5	1960	[2] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^+ MM^-$
1270 ±10	360	[2] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^0 MM$
1268 ± 6		[8] JOHNSON	68	HBC	$3.7–4.2\ \pi^- p$

[1] T-matrix pole.
[2] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[3] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[4] From an energy-independent partial-wave analysis.
[5] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$.
[6] From an amplitude analysis of $\pi^+\pi^- \to \pi^+\pi^-$ scattering data.
[7] Systematic uncertainties not estimated.
[8] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.

$f_2(1270)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$185.5^{+3.8}_{-2.7}$ OUR FIT Error includes scale factor of 1.5.				
$184.6^{+4.2}_{-2.6}$ OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.				
204 ±20		[9] BERTIN	97C	OBLX $0.0\ \overline{p}p \rightarrow \pi^+\pi^-\pi^0$
192 ± 5	200k	PROKOSHKIN	94	GAM2 $38\ \pi^- p \rightarrow \pi^0\pi^0 n$
180 ±24		AGUILAR-...	91	EHS $400\ pp$
169 ± 9	5730	[10] AUGUSTIN	89	DM2 $e^+e^- \rightarrow 5\pi$
150 ±30	400	[10] ALDE	87	GAM4 $100\ \pi^- p \rightarrow 4\pi^0 n$
$186\ ^{+9}_{-2}$		[11] LONGACRE	86	MPS $22\ \pi^- p \rightarrow n2K^0_S$
$179.2^{+6.9}_{-6.6}$		[12] CHABAUD	83	ASPK $17\ \pi^- p$ polarized
160 ±11		DENNEY	83	LASS $10\ \pi^+ N$
196 ±10	3k	APEL	82	CNTR $25\ \pi^- p \rightarrow n2\pi^0$
152 ± 9		[13] CASON	82	STRC $8\ \pi^+ p \rightarrow \Delta^{++}\pi^0\pi^0$
186 ±27	11600	GIDAL	81	MRK2 J/ψ decay
216 ±13		[14] CORDEN	79	OMEG $12–15\ \pi^- p \rightarrow n2\pi$
190 ±10	10k	APEL	75	NICE $40\ \pi^- p \rightarrow n2\pi^0$
192 ±16	4600	ENGLER	74	DBC $6\ \pi^+ n \rightarrow \pi^+\pi^- p$
183 ±15	5300	FLATTE	71	HBC $7\ \pi^+ p \rightarrow \Delta^{++} f_2$
196 ±30		[10] STUNTEBECK	70	HBC $8\ \pi^- p$, $5.4\ \pi^+ d$
216 ±20	1960	[10] ARMENISE	68	DBC $5.1\ \pi^+ n \rightarrow p\pi^+ MM^-$
128 ±27		[10] BOESEBECK	68	HBC $8\ \pi^+ p$
176 ±21		[10,15] JOHNSON	68	HBC $3.7–4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
187 ±20		[16] ALDE	97	GAM2 $450\ pp \rightarrow pp\pi^0\pi^0$
184 ±10		[16] GRYGOREV	96	SPEC $40\ \pi^- N \rightarrow K^0_S K^0_S X$
200 ±10		AKER	91	CBAR $0.0\ \overline{p}p \rightarrow 3\pi^0$
240 ±40	3k	BINON	83	GAM2 $38\ \pi^- p \rightarrow n2\eta$
187 ±30	650	[10] ANTIPOV	77	CIBS $25\ \pi^- p \rightarrow p3\pi$
225 ±38	16000	DEUTSCH...	76	HBC $16\ \pi^+ p$
166 ±28	600	[10] TAKAHASHI	72	HBC $8\ \pi^- p \rightarrow n2\pi$
173 ±53		[10] ARMENISE	70	HBC $9\ \pi^+ n \rightarrow p\pi^+\pi^-$

[9] T-matrix pole.

[10] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[11] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

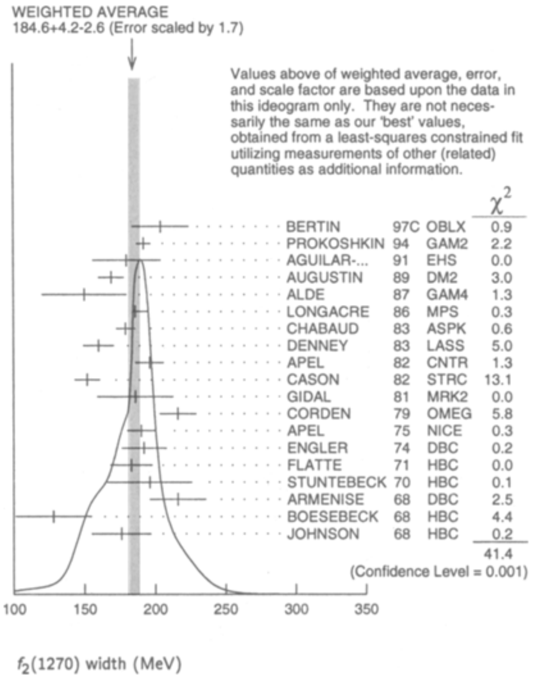
[12] From an energy-independent partial-wave analysis.

[13] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$.

[14] From an amplitude analysis of $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering data.

[15] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.

[16] Systematic uncertainties not estimated.



$f_2(1270)$ width (MeV)

$f_2(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$(84.6\ ^{+2.5}_{-1.3})\ \%$	S=1.3
Γ_2	$\pi^+\pi^- 2\pi^0$	$(\ 7.2\ ^{+1.5}_{-2.7})\ \%$	S=1.3
Γ_3	$K\overline{K}$	$(\ 4.6\ \pm 0.4\ )\ \%$	S=2.8
Γ_4	$2\pi^+ 2\pi^-$	$(\ 2.8\ \pm 0.4\ )\ \%$	S=1.2
Γ_5	$\eta\eta$	$(\ 4.5\ \pm 1.0\ ) \times 10^{-3}$	S=2.4
Γ_6	$4\pi^0$	$(\ 3.0\ \pm 1.0\ ) \times 10^{-3}$	
Γ_7	$\gamma\gamma$	$(\ 1.32^{+0.17}_{-0.16}) \times 10^{-5}$	
Γ_8	$\eta\pi\pi$	$< 8 \times 10^{-3}$	CL=95%
Γ_9	$K^0 K^- \pi^+ +$ c.c.	$< 3.4 \times 10^{-3}$	CL=95%
Γ_{10}	e^+e^-	$< 9 \times 10^{-9}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, a combination of partial widths obtained from integrated cross sections, and 6 branching ratios uses 39 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 70.7$ for 32 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccccccc}
x_2 & -92 & & & & & & \\
x_3 & 11 & -38 & & & & & \\
x_4 & 11 & -36 & 1 & & & & \\
x_5 & 2 & -9 & 0 & 0 & & & \\
x_6 & 0 & -7 & 0 & 0 & 0 & & \\
x_7 & 8 & -3 & -15 & 1 & 0 & 0 & \\
\Gamma & -79 & 74 & -12 & -9 & -3 & 0 & -10 \\
\hline
 & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7
\end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi\pi$	$156.9\ ^{+4.2}_{-1.2}$	
Γ_2	$\pi^+\pi^- 2\pi^0$	$13.4\ ^{+3.1}_{-5.1}$	1.3
Γ_3	$K\overline{K}$	$8.6\ \pm 0.8$	2.9
Γ_4	$2\pi^+ 2\pi^-$	$5.2\ \pm 0.7$	1.2
Γ_5	$\eta\eta$	$0.83\ \pm 0.18$	2.4
Γ_6	$4\pi^0$	$0.55\ \pm 0.19$	
Γ_7	$\gamma\gamma$	$0.00244^{+0.00032}_{-0.00029}$	

$f_2(1270)$ PARTIAL WIDTHS

$\Gamma(\pi\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$156.9^{+4.2}_{-1.2}$ OUR FIT			
$157.0^{+6.0}_{-1.0}$	[17] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(K\overline{K})$ Γ_3

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
8.6 ±0.8 OUR FIT Error includes scale factor of 2.9.			
$9.0\ ^{+0.7}_{-0.3}$	[17] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(\eta\eta)$ Γ_5

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.83±0.18 OUR FIT Error includes scale factor of 2.4.			
1.0 ±0.1	[17] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(\gamma\gamma)$ Γ_7

The value of this width depends on the theoretical model used. Unitarised models with scalars give values clustering around ≃ 2.6; without an *S*-wave contribution, values are systematically higher (typically around 3). Since it is used to average results obtained with variety of models, we prefer to quote our own estimate.

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
2.8 ±0.4 OUR ESTIMATE				
$2.44^{+0.32}_{-0.29}$ OUR FIT				
$2.80\pm 0.13^{+0.36}_{-0.27}$		[18] BEHREND 92	CELL	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.10\pm0.35\pm0.35$		[19] BLINOV	92	MD1	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.27\pm0.47\pm0.11$		ADACHI	90D	TOPZ	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.15\pm0.04\pm0.39$		BOYER	90	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.19\pm0.16^{+0.29}_{-0.28}$		MARSISKE	90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0$
2.35 ± 0.65		[20] MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
$3.19\pm0.09^{+0.22}_{-0.38}$	2177	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$
$3.2\pm0.1\pm0.4$		[21] AIHARA	86B	TPC	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.5\pm0.1\pm0.5$		BEHREND	84B	CELL	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.85\pm0.25\pm0.5$		[22] BERGER	84	PLUT	$e^+e^- \to e^+e^-2\pi$
$2.70\pm0.05\pm0.20$		COURAU	84	DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.52\pm0.13\pm0.38$		[23] SMITH	84C	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
$2.7\pm0.2\pm0.6$		EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\pi^0$
$2.9^{+0.6}_{-0.4}\pm0.6$		[24] EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\pi^0$
$3.2\pm0.2\pm0.6$		BRANDELIK	81B	TASS	$e^+e^- \to e^+e^-\pi^+\pi^-$
$3.6\pm0.3\pm0.5$		ROUSSARIE	81	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
2.3 ± 0.8		[25] BERGER	80B	PLUT	e^+e^-

$\Gamma(e^+e^-)$ Γ_{10}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.7	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

[17] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[18] Using a unitarized model with scalars.
[19] Using the unitarized model of LYTH 85.
[20] Error includes spread of different solutions. Data of MARK2 and CRYSTAL BALL used in the analysis. Authors report strong correlations with $\gamma\gamma$ width of $f_0(1370)$: $\Gamma(f_2) + 1/4\, \Gamma(f^0) = 3.6 \pm 0.3$ KeV.
[21] Radiative corrections modify the partial widths; for instance the COURAU 84 value becomes 2.66 ± 0.21 in the calculation of LANDRO 86.
[22] Using the MENNESSIER 83 model.
[23] Superseded by BOYER 90.
[24] If helicity = 2 assumption is not made.
[25] Using mass, width and $B(f_2(1270) \to 2\pi)$ from PDG 78.

$f_2(1270)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_3\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
$0.113^{+0.016}_{-0.015}$ OUR FIT Error includes scale factor of 1.1.				
$0.091\pm0.007\pm0.027$	[26] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.104\pm0.007\pm0.072$	[27] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$

[26] Using an incoherent background.
[27] Using a coherent background.

$f_2(1270)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.846^{+0.025}_{-0.013}$ OUR FIT Error includes scale factor of 1.3.					
0.837 ± 0.020 OUR AVERAGE					
0.849 ± 0.025		CHABAUD	83	ASPK	$17\ \pi^-p$ polarized
0.85 ± 0.05	250	BEAUPRE	71	HBC	$8\ \pi^+p \to \Delta^{++}f_2$
0.8 ± 0.04	600	OH	70	HBC	$1.26\ \pi^-p \to \pi^+\pi^-n$

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(\pi\pi)$ Γ_2/Γ_1

Should be twice $\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ if decay is $\rho\rho$. (See ASCOLI 68D.)

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.085^{+0.020}_{-0.034}$ OUR FIT Error includes scale factor of 1.3.					
0.15 ± 0.06	600	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.07		EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_3/Γ_1

We average only experiments which either take into account $f_2(1270)$-$a_2(1320)$ interference explicitly or demonstrate that $a_2(1320)$ production is negligible.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.055^{+0.005}_{-0.006}$ OUR FIT Error includes scale factor of 2.8.					
$0.040^{+0.005}_{-0.006}$ OUR AVERAGE					
$0.037^{+0.008}_{-0.021}$		ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
0.045 ± 0.009		CHABAUD	81	ASPK	$17\ \pi^-p$ polarized
0.039 ± 0.008		LOVERRE	80	HBC	$4\ \pi^-p \to K\overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.036 ± 0.005		[28] COSTA...	80	OMEG	1–$2.2\ \pi^-p \to K^+K^-n$
0.030 ± 0.005		[29] MARTIN	79	RVUE	
0.027 ± 0.009		[30] POLYCHRO...	79	STRC	$7\ \pi^-p \to n2K^0_S$
0.025 ± 0.015		EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
0.031 ± 0.012	20	ADERHOLZ	69	HBC	$8\ \pi^+p \to K^+K^-\pi^+p$

[28] Re-evaluated by CHABAUD 83.
[29] Includes PAWLICKI 77 data.
[30] Takes into account the $f_2(1270)$-$f'_2(1525)$ interference.

$\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.033 ± 0.005 OUR FIT Error includes scale factor of 1.2.					
0.033 ± 0.004 OUR AVERAGE Error includes scale factor of 1.1.					
0.024 ± 0.006	160	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
0.051 ± 0.025	70	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$
$0.043^{+0.007}_{-0.011}$	285	LOUIE	74	HBC	$3.9\ \pi^-p \to nf_2$
0.037 ± 0.007	154	ANDERSON	73	DBC	$6\ \pi^+n \to pf_2$
0.047 ± 0.013		OH	70	HBC	$1.26\ \pi^-p \to \pi^+\pi^-n$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
4.5 ± 1.0 OUR FIT Error includes scale factor of 2.4.				
3.1 ± 0.8 OUR AVERAGE Error includes scale factor of 1.3.				
2.8 ± 0.7	ALDE	86D	GAM4	$100\ \pi^-p \to 2\eta n$
5.2 ± 1.7	BINON	83	GAM2	$38\ \pi^-p \to 2\eta n$

$\Gamma(\eta\eta)/\Gamma(\pi\pi)$ Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	95	EDWARDS	82F	CBAL	$e^+e^- \to e^+e^-2\eta$
<0.016	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$
<0.09	95	EISENBERG	74	HBC	$4.9\ \pi^+p \to \Delta^{++}f_2$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0030 ± 0.0010 OUR FIT					
0.003 ± 0.001	400 ± 50	ALDE	87	GAM4	$100\ \pi^-p \to 4\pi^0n$

$\Gamma(\eta\pi\pi)/\Gamma(\pi\pi)$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.010	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$\Gamma(K^0K^-\pi^+ + \text{c.c.})/\Gamma(\pi\pi)$ Γ_9/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	95	EMMS	75D	DBC	$4\ \pi^+n \to pf_2$

$f_2(1270)$ REFERENCES

ALDE	97	PL B397 350	+Bellazzini, Binon+	(GAMS Collab.)
BERTIN	97C	PL B408 476	A. Bertin, Bruschi+	(OBELIX Collab.)
GRYGOREV	96	PAN 59 2105 Translated from YAF 59 2187.	+Baloshin, Barkov	(ITEP)
PROKOSHKIN	94	SPD 39 420 Translated from DANS 336 613.	+Kondashov	(SERP)
BEHREND	92	ZPHY C56 381		(CELLO Collab.)
BLINOV	92	ZPHY C53 33	+Bondar, Bukin+	(NOVO)
AGUILAR-...	91	ZPHY C50 405	Aguilar-Benitez, Allison, Batalor+	(LEBC-EHS Collab.)
AKER	91	PL B260 249	+Amsler, Peters+	(Crystal Barrel Collab.)
ADACHI	90D	PL B234 185	+Doser+	(TOPAZ Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEIDH, WARS)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
LANDRO	86	PL B172 445	+Mork, Olsen	(UTRO)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
LYTH	85	JPG 11 459		
BEHREND	84B	ZPHY C23 223	+Fenner, Schachter, Schroeder+	(CELLO Collab.)
BERGER	84	ZPHY C26 199	+Klovning, Burger+	(PLUTO Collab.)
COURAU	84	PL 147B 227	+Johnson, Sherman, Atwood, Baillon+	(CIT, SLAC)
SMITH	84C	PR D30 851	+Burke, Abrams, Blocker, Levi+	(SLAC, LBL, HARV)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
Also	83B	SJNP 38 561 Translated from YAF 38 934.	Binon, Gouanere+	(BELG, LAPP, SERP, CERN)
CHABAUD	83	NP B223 1	+Gorlich, Cerrada+	(CERN, CRAC, MPIM)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
MENNESSIER	83	ZPHY C16 241		(MONP)
APEL	82	NP B201 197	+Augenstein+	(KARLK, KARLE, PISA, SERP, WIEN, CERN)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
EDWARDS	82F	PL 110B 82	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
BRANDELIK	81B	ZPHY C10 117	+Boerner+	(TASSO Collab.)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)

GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
ROUSSARIE	81	PL 105B 304	+Burke, Abrams, Alam+	(SLAC, LBL)
BERGER	80B	PL 94B 254	+Genzer+	(PLUTO Collab.)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
PDG	78	PL 75B	Bricman+	
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL)
DEUTSCH...	76	NP B103 426	Deutschmann+	(AACH3, BERL, BONN, CERN+)
APEL	75	PL 57B 398	+Augenstein+	(KARLK, KARLE, PISA, SERP, WIEN, CERN)
EMMS	75D	NP B96 155	+Kinson, Stacey, Votruba+	(BIRM, DURH, RHEL)
EISENBERG	74	PL 52B 239	+Engler, Haber, Karshon+	(REHO)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
LOUIE	74	PL 48B 385	+Alitti, Gandois, Chaloupka+	(SACL, CERN)
ANDERSON	73	PRL 31 562	+Engler, Kraemer, Toaff, Diaz+	(CMU, CASE)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHOK, PENN, NDAM, ANL)
BEAUPRE	71	NP B28 77	+Deutschmann, Graessler+	(AACH, BERL, CERN)
FLATTE	71	PL 34B 551	+Alston-Garnjost, Barbaro-Galtieri+	(LBL)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)
OH	70	PR D1 2494	+Garfinkel, Morse, Walker, Prentice	(WISC, TNTO) JP
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+	(NDAM)
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH3, BERL, CERN, JAGL, WARS)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSAY)
ASCOLI	68D	PRL 21 1712	+Crawley, Mortara+	(ILL)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
JOHNSON	68	PR 176 1651	+Poirier, Biswas, Gutay+	(NDAM, PURD, SLAC)
EISNER	67	PR 164 1699	+Johnson, Klein, Peters, Sahni, Yen+	(PURD)
DERADO	65	PRL 14 872	+Kenney, Poirier, Shephard	(NDAM)
LEE	64	PRL 12 342	+Roe, Sinclair, VanderVelde	(MICH)
BONDAR	63	PL 5 153	+	(AACH, BIRM, BONN, DESY, LOIC, MPIM)

$f_1(1285)$

$I^G(J^{PC}) = 0^+(1^{++})$

$f_1(1285)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1281.9 ± 0.6 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.		
1284 ± 6	1400	ALDE 97B	GAM4	100 $\pi^- p \to \eta\pi^0\pi^0 n$
1281 ± 1		BARBERIS 97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
1281 ± 1		BARBERIS 97C	OMEG	450 $pp \to ppK^0_S K^\pm \pi^\mp$
1280 ± 2		[1] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
1282.2 ± 1.5		LEE 94	MPS2	18 $\pi^- p \to K^+\overline{K}^0 2\pi^- p$
1279 ± 5		FUKUI 91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
1278 ± 2	140	ARMSTRONG 89	OMEG	300 $pp \to K\overline{K}\pi pp$
1278 ± 2		ARMSTRONG 89G	OMEG	85 $\pi^+ p \to 4\pi\pi p$, $pp \to 4\pi pp$
1280.1 ± 2.1	60	RATH 89	MPS	21.4 $\pi^- p \to K^0_S K^0_S \pi^0 n$
1285 ± 1	4750	[2] BIRMAN 88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
1280 ± 1	504	BITYUKOV 88	SPEC	32.5 $\pi^- p \to K^+K^-\pi^0 n$
1280 ± 4		ANDO 86	SPEC	8 $\pi^- p \to \eta\pi^+\pi^- n$
1277 ± 2	420	REEVES 86	SPEC	6.6 $p\overline{p} \to KK\pi X$
1285 ± 2		CHUNG 85	SPEC	8 $\pi^- p \to NK\overline{K}\pi$
1279 ± 2	604	ARMSTRONG 84	OMEG	85 $\pi^+ p \to K\overline{K}\pi\pi p$, $pp \to K\overline{K}\pi pp$
1286 ± 1		CHAUVAT 84	SPEC	ISR 31.5 pp
1278 ± 4		EVANGELISTA 81	OMEG	12 $\pi^- p \to \eta\pi^+\pi^-\pi^- p$
1283 ± 3	103	DIONISI 80	HBC	4 $\pi^- p \to K\overline{K}\pi n$
1282 ± 2	320	NACASCH 78	HBC	0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$
1279 ± 5	210	GRASSLER 77	HBC	16 $\pi^\mp p$
1286 ± 3	180	DUBOC 72	HBC	1.2 $\overline{p}p \to 2K4\pi$
1283 ± 5		DAHL 67	HBC	1.6–4.2 $\pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1270 ± 10		AMELIN 95	VES	37 $\pi^- N \to \pi^-\pi^+\pi^-\gamma N$
1280 ± 2		ABATZIS 94	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
1282 ± 4		ARMSTRONG 93C	E760	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
1270 ± 6 ± 10		ARMSTRONG 92C	OMEG	300 $pp \to pp\pi^+\pi^-\gamma$
1264 ± 8		AUGUSTIN 90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
1281 ± 1		ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$
1279 ± 6 ± 10	16	BECKER 87	MRK3	$e^+e^- \to \phi K\overline{K}\pi$
1286 ± 9		GIDAL 87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
1287 ± 5	353	BITYUKOV 84B	SPEC	32 $\pi^- p \to K^+K^-\pi^0 n$
~ 1279		[3] TORNQVIST 82B	RVUE	
1275 ± 6	31	BROMBERG 80	SPEC	100 $\pi^- p \to K\overline{K}\pi X$
1288 ± 9	200	GURTU 79	HBC	4.2 $K^- p \to n\eta 2\pi$
~ 1275.0	46	[4] STANTON 79	CNTR	8.5 $\pi^- p \to n2\gamma 2\pi$
1271 ± 10	34	CORDEN 78	OMEG	12–15 $\pi^- p \to K^+K^-\pi n$
1295 ± 12	85	CORDEN 78	OMEG	12–15 $\pi^- p \to n5\pi$
1292 ± 10	150	DEFOIX 72	HBC	0.7 $\overline{p}p \to 7\pi$
1280 ± 3	500	[5] THUN 72	MMS	13.4 $\pi^- p$
1303 ± 8		BARDADIN-... 71	HBC	8 $\pi^+ p \to p6\pi$
1283 ± 6		BOESEBECK 71	HBC	16.0 $\pi p \to p5\pi$
1270 ± 10		CAMPBELL 69	DBC	2.7 $\pi^+ d$
1285 ± 7		LORSTAD 69	HBC	0.7 $\overline{p}p$, 4,5-body
1290 ± 7		D'ANDLAU 68	HBC	1.2 $\overline{p}p$, 5–6 body

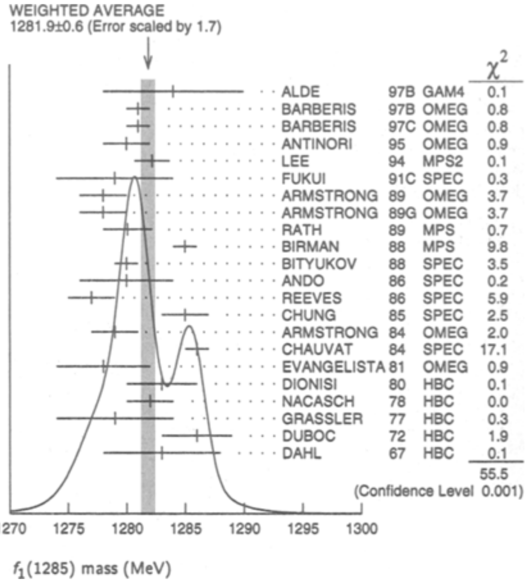
[1] Supersedes ABATZIS 94, ARMSTRONG 89E.

[2] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.

[3] From a unitarized quark-model calculation.

[4] From phase shift analysis of $\eta\pi^+\pi^-$ system.

[5] Seen in the missing mass spectrum.



$f_1(1285)$ WIDTH

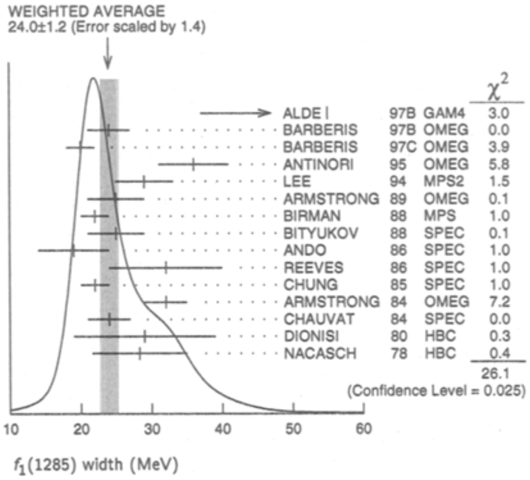
Only experiments giving width error less than 20 MeV are kept for averaging.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
24.0 ± 1.2 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
55 ± 18	1400	ALDE 97B	GAM4	100 $\pi^- p \to \eta\pi^0\pi^0 n$
24 ± 3		BARBERIS 97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
20 ± 2		BARBERIS 97C	OMEG	450 $pp \to ppK^0_S K^\pm\pi^\mp$
36 ± 5		[6] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
29.0 ± 4.1		LEE 94	MPS2	18 $\pi^- p \to K^+\overline{K}^0 2\pi^- p$
25 ± 4	140	ARMSTRONG 89	OMEG	300 $pp \to K\overline{K}\pi pp$
22 ± 2	4750	[7] BIRMAN 88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
25 ± 4	504	BITYUKOV 88	SPEC	32.5 $\pi^- p \to K^+K^-\pi^0 n$
19 ± 5		ANDO 86	SPEC	8 $\pi^- p \to \eta\pi^+\pi^- n$
32 ± 8	420	REEVES 86	SPEC	6.6 $p\overline{p} \to KK\pi X$
22 ± 2		CHUNG 85	SPEC	8 $\pi^- p \to NK\overline{K}\pi$
32 ± 3	604	ARMSTRONG 84	OMEG	85 $\pi^+ p \to K\overline{K}\pi\pi p$, $pp \to K\overline{K}\pi pp$
24 ± 3		CHAUVAT 84	SPEC	ISR 31.5 pp
29 ± 10	103	DIONISI 80	HBC	4 $\pi^- p \to K\overline{K}\pi n$
28.3 ± 6.7	320	NACASCH 78	HBC	0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

40 ± 5		ABATZIS	94	OMEG	450 $pp \rightarrow pp2(\pi^+\pi^-)$
44 ±20		AUGUSTIN	90	DM2	$J/\psi \rightarrow \gamma\eta\pi^+\pi^-$
31 ± 5		ARMSTRONG	89E	OMEG	300 $pp \rightarrow pp2(\pi^+\pi^-)$
41 ±12		ARMSTRONG	89G	OMEG	85 $\pi^+ p \rightarrow 4\pi\pi p$, $pp \rightarrow 4\pi pp$
17.9±10.9	60	RATH	89	MPS	21.4 $\pi^- p \rightarrow K^0_S K^0_S \pi^0 n$
14 $^{+20}_{-14}$ ±10	16	BECKER	87	MRK3	$e^+e^- \rightarrow \phi K\overline{K}\pi$
26 ±12		EVANGELISTA	81	OMEG	12 $\pi^- p \rightarrow \eta\pi^+\pi^-\pi^- p$
25 ±15	200	GURTU	79	HBC	4.2 $K^- p \rightarrow n\eta 2\pi$
~ 10		[8] STANTON	79	CNTR	8.5 $\pi^- p \rightarrow n2\gamma 2\pi$
24 ±18	210	GRASSLER	77	HBC	16 $\pi^\mp p$
28 ± 5	150	[9] DEFOIX	72	HBC	0.7 $\overline{p}p \rightarrow 7\pi$
46 ± 9	180	[9] DUBOC	72	HBC	1.2 $\overline{p}p \rightarrow 2K4\pi$
37 ± 5	500	[10] THUN	72	MMS	13.4 $\pi^- p$
10 ±10		BOESEBECK	71	HBC	16.0 $\pi p \rightarrow p5\pi$
30 ±15		CAMPBELL	69	DBC	2.7 $\pi^+ d$
60 ±15		[9] LORSTAD	69	HBC	0.7 $\overline{p}p$, 4,5-body
35 ±10		[9] DAHL	67	HBC	1.6–4.2 $\pi^- p$

[6] Supersedes ABATZIS 94, ARMSTRONG 89E.
[7] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.
[8] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[9] Resolution is not unfolded.
[10] Seen in the missing mass spectrum.



$f_1(1285)$ DECAY MODES

$(4\pi = \rho(\pi\pi)_{Pwave})$

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	4π	(35 ± 4) %	S=1.6
Γ_2	$\pi^0\pi^0\pi^+\pi^-$	(23.5± 3.0) %	S=1.6
Γ_3	$2\pi^+2\pi^-$	(11.7± 1.5) %	S=1.6
Γ_4	$\rho^0\pi^+\pi^-$	(11.7± 1.5) %	S=1.6
Γ_5	$4\pi^0$	< 7 × 10^{-4}	CL=90%
Γ_6	$\eta\pi\pi$	(50 ±18) %	
Γ_7	$a_0(980)\pi$ [ignoring $a_0(980) \rightarrow K\overline{K}$]	(34 ± 8) %	S=1.2
Γ_8	$\eta\pi\pi$ [excluding $a_0(980)\pi$]	(15 ± 7) %	S=1.1
Γ_9	$K\overline{K}\pi$	(9.6± 1.2) %	S=1.5
Γ_{10}	$K\overline{K}^*(892)$	not seen	
Γ_{11}	$\gamma\rho^0$	(5.4± 1.2) %	S=2.3
Γ_{12}	$\phi\gamma$	(7.9± 3.0) × 10^{-4}	
Γ_{13}	$\gamma\gamma^*$		
Γ_{14}	$\gamma\gamma$		

CONSTRAINED FIT INFORMATION

An overall fit to 7 branching ratios uses 14 measurements and one constraint to determine 5 parameters. The overall fit has a χ^2 = 23.7 for 10 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cccc}
x_7 & -48 & & & \\
x_8 & -24 & -72 & & \\
x_9 & 89 & -45 & -22 & \\
x_{11} & -5 & -8 & -4 & -6 \\
\hline
 & x_1 & x_7 & x_8 & x_9
\end{array}$$

$f_1(1285)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\quad\Gamma_6\Gamma_{14}/\Gamma = (\Gamma_7+\Gamma_8)\Gamma_{14}/\Gamma$

VALUE (keV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.62	95	GIDAL	87	MRK2	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{\text{total}}$ $\quad\Gamma_6\Gamma_{13}/\Gamma = (\Gamma_7+\Gamma_8)\Gamma_{13}/\Gamma$

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.4 ±0.4 OUR AVERAGE Error includes scale factor of 1.4.					
1.18±0.25±0.20	26	[11,12] AIHARA	88B	TPC	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$
2.30±0.61±0.42		[11,13] GIDAL	87	MRK2	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$

[11] Assuming a ρ-pole form factor.
[12] Published value multiplied by $\eta\pi\pi$ branching ratio 0.49.
[13] Published value divided by 2 and multiplied by the $\eta\pi\pi$ branching ratio 0.49.

$f_1(1285)$ BRANCHING RATIOS

$\Gamma(K\overline{K}\pi)/\Gamma(4\pi)$ $\quad\Gamma_9/\Gamma_1$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.274±0.018 OUR FIT Error includes scale factor of 1.4.				
0.271±0.016 OUR AVERAGE Error includes scale factor of 1.2.				
0.265±0.014	[14] BARBERIS	97C	OMEG	450 $pp \rightarrow ppK^0_S K^\pm\pi^\mp$
0.28 ±0.05	[15] ARMSTRONG	89E	OMEG	300 $pp \rightarrow ppf_1(1285)$
0.37 ±0.03 ±0.05	[16] ARMSTRONG	89G	OMEG	85 $\pi p \rightarrow 4\pi X$

[14] Using $2(\pi^+\pi^-)$ data from BARBERIS 97B.
[15] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.
[16] 4π consistent with being entirely $\rho\pi\pi$.

$\Gamma(\pi^0\pi^0\pi^+\pi^-)/\Gamma_{\text{total}}$ $\quad\Gamma_2/\Gamma = \frac{2}{3}\Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*
0.235±0.030 OUR FIT Error includes scale factor of 1.6.	

$\Gamma(2\pi^+2\pi^-)/\Gamma_{\text{total}}$ $\quad\Gamma_3/\Gamma = \frac{1}{3}\Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*
0.117±0.015 OUR FIT Error includes scale factor of 1.6.	

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ $\quad\Gamma_4/\Gamma = \frac{1}{3}\Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*
0.117±0.015 OUR FIT Error includes scale factor of 1.6.	

$\Gamma(K\overline{K}\pi)/\Gamma(\eta\pi\pi)$ $\quad\Gamma_9/\Gamma_6 = \Gamma_9/(\Gamma_7+\Gamma_8)$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.19±0.04 OUR FIT Error includes scale factor of 1.4.				
0.23±0.06 OUR AVERAGE Error includes scale factor of 1.2.				
0.42±0.15	GURTU	79	HBC	4.2 $K^- p$
0.5 ±0.2	CORDEN	78	OMEG	12–15 $\pi^- p$
0.20±0.08	[17] DEFOIX	72	HBC	0.7 $\overline{p}p \rightarrow 7\pi$
0.16±0.08	CAMPBELL	69	DBC	2.7 $\pi^+ d$

[17] $K\overline{K}$ system characterized by the $I = 1$ threshold enhancement. (See under $a_0(980)$).

$\Gamma(a_0(980)\pi$ [ignoring $a_0(980) \rightarrow K\overline{K}$]$)/\Gamma(\eta\pi\pi)$ $\quad\Gamma_7/\Gamma_6 = \Gamma_7/(\Gamma_7+\Gamma_8)$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.69±0.13 OUR FIT					
0.69$^{+0.13}_{-0.12}$ OUR AVERAGE					
0.72±0.15		GURTU	79	HBC	4.2 $K^- p$
0.6 $^{+0.3}_{-0.2}$		CORDEN	78	OMEG	12–15 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.28±0.07	1400	ALDE	97B	GAM4	100 $\pi^- p \rightarrow \eta\pi^0\pi^0 n$
1.0 ±0.3		GRASSLER	77	HBC	16 $\pi^\mp p$

$\Gamma(4\pi)/\Gamma(\eta\pi\pi)$ $\Gamma_1/\Gamma_6 = \Gamma_1/(\Gamma_7+\Gamma_8)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.71±0.15 OUR FIT Error includes scale factor of 1.5.			
0.41±0.14 OUR AVERAGE			
0.37±0.11±0.11	BOLTON 92	MRK3	$J/\psi \rightarrow \gamma f_1(1285)$
0.64±0.40	GURTU 79	HBC	4.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.93±0.30	[18] GRASSLER 77	HBC	16 $\pi^\mp p$

[18] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.

$\Gamma(K\overline{K}^*(892))/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	NACASCH 78	HBC	0.7,0.76 $\overline{p}p \rightarrow K\overline{K}3\pi$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2\pi^+2\pi^-)$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.0±0.4	GRASSLER 77	HBC	16 GeV $\pi^\pm p$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<7	90	ALDE 87	GAM4	100 $\pi^- p \rightarrow 4\pi^0 n$

$\Gamma(\phi\gamma)/\Gamma(K\overline{K}\pi)$ Γ_{12}/Γ_9

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.82±0.21±0.20		19	BITYUKOV 88	SPEC	32.5 $\pi^- p \rightarrow K^+ K^- \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.93	95		AMELIN 95	VES	37 $\pi^- N \rightarrow \pi^-\pi^+\pi^-\gamma N$

$\Gamma(\gamma\rho^0)/\Gamma(K\overline{K}\pi)$ Γ_{11}/Γ_9

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.035	90	[19] COFFMAN 90	MRK3	$J/\psi \rightarrow \gamma\gamma\pi^+\pi^-$

[19] Using $B(J/\psi \rightarrow \gamma f_1(1285) \rightarrow \gamma\gamma\rho^0)=0.25 \times 10^{-4}$ and $B(J/\psi \rightarrow \gamma f_1(1285) \rightarrow \gamma K\overline{K}\pi)=< 0.72 \times 10^{-3}$.

$\Gamma(\gamma\rho^0)/\Gamma(2\pi^+2\pi^-)$ $\Gamma_{11}/\Gamma_3 = \Gamma_{11}/\frac{1}{3}\Gamma_1$

VALUE	DOCUMENT ID	TECN	COMMENT
0.46±0.13 OUR FIT Error includes scale factor of 1.9.			
0.45±0.18	[20] COFFMAN 90	MRK3	$J/\psi \rightarrow \gamma\gamma\pi^+\pi^-$

[20] Using $B(J/\psi \rightarrow \gamma f_1(1285) \rightarrow \gamma\gamma\rho^0)=0.25 \times 10^{-4}$ and $B(J/\psi \rightarrow \gamma f_1(1285) \rightarrow \gamma 2\pi^+ 2\pi^-)=0.55 \times 10^{-4}$ given by MIR 88.

$\Gamma(\gamma\rho^0)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.054±0.012 OUR FIT Error includes scale factor of 2.3.				
0.028±0.007±0.006		AMELIN 95	VES	37 $\pi^- N \rightarrow \pi^-\pi^+\pi^-\gamma N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	95	BITYUKOV 91B	SPEC	32 $\pi^- p \rightarrow \pi^+\pi^-\gamma n$

$\Gamma(\eta\pi\pi)/\Gamma(\gamma\rho^0)$ $\Gamma_6/\Gamma_{11} = (\Gamma_7+\Gamma_8)/\Gamma_{11}$

VALUE	DOCUMENT ID	TECN	COMMENT
9.2±2.6 OUR FIT Error includes scale factor of 3.0.			
7.5±1.0	[21] ARMSTRONG 92C	OMEG	300 $pp \rightarrow pp\pi^+\pi^-\gamma$, $pp\eta\pi^+\pi^-$

[21] Published value multiplied by 1.5.

$f_1(1285)$ REFERENCES

ALDE	97B	PAN 60 386	D. Alde, Binon, Bricman+	(GAMS Collab.)	
		Translated from YAF 60 458.			
BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)	
BARBERIS	97C	PL B413 225	D. Barberis+	(WA102 Collab.)	
AMELIN	95	ZPHY C66 71	+Berdnikov+	(VES Collab.)	
ANTINORI	95	PL B353 589	+Barberis, Bayes+	(ATHU, BARI, BIRM, CERN, JINR)	
ABATZIS	94	PL B324 509	+Antinori, Barberis+	(ATHU, BARI, BIRM, CERN, JINR)	
LEE	94	PL B323 227	+Chung, Kirk+	(BNL, IND, KYUN, MASD, RICE)	
ARMSTRONG	93C	PL B307 394	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)	
ARMSTRONG	92C	ZPHY C54 371	+Barnes, Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)	
BOLTON	92	PL B278 495	+Brown, Bunnell+	(Mark III Collab.)	
BITYUKOV	91B	SJNP 54 318	+Borisov, Viktorov+	(SERP)	
		Translated from YAF 54 529.			
FUKUI	91C	PL B267 293	+	(SUGI, NAGO, KEK, KYOT, MIYA, AKIT)	
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)	
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)	
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)	JPC
ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, CURIN+)	
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)	
RATH	89	PR D40 693	+Cason+	(NDAM, BRAN, BNL, CUNY, DUKE)	
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)	
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, MASD)	JP
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)	
MIR	88	Photon-Photon 88 Conf., 126		(Mark III Collab.)	
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)	
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)	
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)	
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+)	IJP
REEVES	86	PR 34 1960	+Chung, Crittenden+	(FLOR, BNL, IND, MASD)	JP
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, MASD)	JP
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)	JP
BITYUKOV	84B	PL 144B 133	Bitukov, Dorofeev, Dzhelyadin, Golovkin, Kulik+	(SERP)	
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, CLER, UCLA, SACL)	
TORNQVIST	82B	NP B203 268		(HELS)	
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)	
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)	
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)	
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)	
STANTON	79	PRL 42 346	+Brockman+	(OSU, CARL, MCGI, TNTO)	JP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)	JP
NACASCH	78	NP B135 203	+Defoix, Dobrzynski+	(PARIS, MADR, CERN)	
GRASSLER	77	NP B121 189	+	(AACH3, BERL, BONN, CERN, CRAC, HEIDH+)	
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)	
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(PARIS, LIVP)	
THUN	72	PRL 28 1733	+Blieden, Finocchiaro, Bowen+	(STON, NEAS)	
BARDADIN-...	71	PR D4 2711	Bardadin-Otwinowska, Hofmokl+	(WARS)	
BOESEBECK	71	PL 34B 659		(AACH, BERL, BONN, CERN, CRAC, HEID, WARS)	
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)	
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN)	JP
D'ANDLAU	68	NP B5 693	+Astier, Barlow+	(CDEF, CERN, IRAD, LIVP)	IJP
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)	IJP

OTHER RELATED PAPERS

AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.)	JPC
ASTON	85	PR D32 2255	+Carnegie, Dunwoodie+	(SLAC, CARL, CNRC)	
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)	
GAVILLET	82	ZPHY C16 119	+Armenteros+	(CERN, CDEF, PADO, ROMA)	
D'ANDLAU	65	PL 17 347	+Barlow, Adamson+	(CDEF, CERN, IRAD, LIVP)	
MILLER	65	PRL 14 1074	+Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)	

$\eta(1295)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\eta(1295)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1297.0±2.8 OUR AVERAGE				
1299 ±4	2100	ALDE 97B	GAM4	100 $\pi^- p \rightarrow \eta\pi^0\pi^0 n$
1295 ±4		FUKUI 91C	SPEC	8.95 $\pi^- p \rightarrow \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1275		STANTON 79	CNTR	8.4 $\pi^- p \rightarrow n\eta 2\pi$

$\eta(1295)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
53±6		FUKUI 91C	SPEC	8.95 $\pi^- p \rightarrow \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<40	2100	ALDE 97B	GAM4	100 $\pi^- p \rightarrow \eta\pi^0\pi^0 n$
~ 70		STANTON 79	CNTR	8.4 $\pi^- p \rightarrow n\eta 2\pi$

$\eta(1295)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^+\pi^-$	seen
Γ_2	$a_0(980)\pi$	seen
Γ_3	$\gamma\gamma$	
Γ_4	$\eta\pi^0\pi^0$	seen
Γ_5	$\eta(\pi\pi)_{S\text{-wave}}$	seen

$\eta(1295)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi^+\pi^-) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.3		ANTREASYAN 87	CBAL	$e^+e^- \rightarrow e^+e^-\eta\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.6	90	AIHARA 88C	TPC	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$

$\eta(1295)$ BRANCHING RATIOS

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen	BERTIN 97	OBLX	0.0 $\overline{p}p \rightarrow K^\pm(K^0)\pi^\mp\pi^+\pi^-$
seen	BIRMAN 88	MPS	8 $\pi^- p \rightarrow K^+\overline{K}^0\pi^- n$
large	ANDO 86	SPEC	8 $\pi^- p \rightarrow \eta\pi^+\pi^- n$
large	STANTON 79	CNTR	8.4 $\pi^- p \rightarrow n\eta 2\pi$

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi^0\pi^0)$ Γ_2/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.65±0.10	[1] ALDE 97B	GAM4	100 $\pi^- p \rightarrow \eta\pi^0\pi^0 n$

[1] Assuming that $a_0(980)$ decays only to $\eta\pi$.

$\Gamma(\eta(\pi\pi)_{S\text{-wave}})/\Gamma(\eta\pi^0\pi^0)$ — Γ_5/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.35±0.10	ALDE 97B	GAM4	$100\ \pi^- p \to \eta\pi^0\pi^0 n$

$\eta(1295)$ REFERENCES

ALDE 97B PAN 60 386 D. Alde, Binon, Bricman+ (GAMS Collab.)
Translated from YAF 60 458.
BERTIN 97 PL B400 226 +Bruschi, Capponi+ (OBELIX Collab.)
FUKUI 91C PL B267 293 + (SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD) JP
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, TSUK+) IJP
STANTON 79 PRL 42 346 +Brockman+ (OSU, CARL, MCGI, TNTO) JP

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

$\pi(1300)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1300±100 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1275± 15	BERTIN 97D	OBLX	$0.05\ \overline{p}p \to 2\pi^+2\pi^-$
~ 1114	ABELE 96	CBAR	$0.0\ \overline{p}p \to 5\pi^0$
1190± 30	ZIELINSKI 84	SPEC	$200\ \pi^+ Z \to Z3\pi$
1240± 30	BELLINI 82	SPEC	$40\ \pi^- A \to A3\pi$
1273± 50	[1] AARON 81	RVUE	
1342± 20	BONESINI 81	OMEG	$12\ \pi^- p \to p3\pi$
~ 1400	DAUM 81B	SPEC	$63,94\ \pi^- p$

[1] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200 to 600 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
218±100	BERTIN 97D	OBLX	$0.05\ \overline{p}p \to 2\pi^+2\pi^-$
~ 340	ABELE 96	CBAR	$0.0\ \overline{p}p \to 5\pi^0$
440± 80	ZIELINSKI 84	SPEC	$200\ \pi^+ Z \to Z3\pi$
360±120	BELLINI 82	SPEC	$40\ \pi^- A \to A3\pi$
580±100	[2] AARON 81	RVUE	
220± 70	BONESINI 81	OMEG	$12\ \pi^- p \to p3\pi$
~ 600	DAUM 81B	SPEC	$63,94\ \pi^- p$

[2] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\pi(\pi\pi)_{S\text{-wave}}$	seen
Γ_3	$\gamma\gamma$	

$\pi(1300)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.085	90	ACCIARRI 97T	L3	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
<0.54	90	ALBRECHT 97B	ARG	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
2.12	[3] AARON 81	RVUE

[3] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ REFERENCES

ACCIARRI 97T PL B413 147 M. Acciarri+
ALBRECHT 97B ZPHY C74 469 +Hamacher, Hofmann+ (ARGUS Collab.)
BERTIN 97D PL B414 220 A. Bertin+ (OBELIX Collab.)
ABELE 96 PL B380 453 +Adomeit, Amsler+ (Crystal Barrel Collab.)
ZIELINSKI 84 PR D30 1855 +Berg, Chandlee, Cihangir+ (ROCH, MINN, FNAL)
BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)
AARON 81 PR D24 1207 +Longacre (NEAS, BNL)
BONESINI 81 PL 103B 75 +Donald+ (MILA, LIVP, DARE, CERN, BARI, BONN)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
DAUM 81B NP B182 269 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DAUM 80 PL 89B 281 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXFTP, DARE)

OTHER RELATED PAPERS

ACKERSTAFF 97R ZPHY C75 593 K. Ackerstaff+ (OPAL Collab.)
ALBRECHT 95C PL B349 576 +Hamacher, Hofmann, Kirchoff+ (ARGUS Collab.)

$a_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

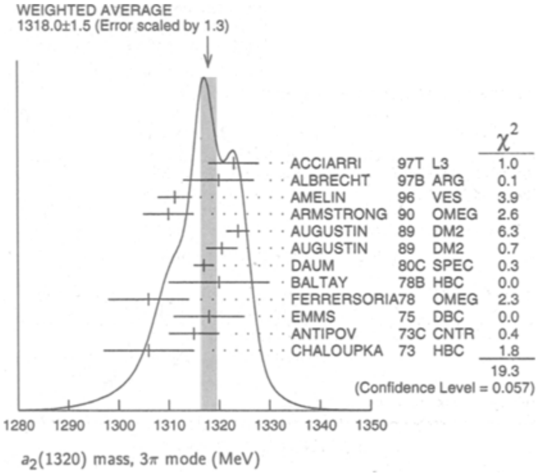
$a_2(1320)$ MASS

VALUE (MeV)	DOCUMENT ID
1318.1±0.6 OUR AVERAGE	Includes data from the 4 datablocks that follow this one. Error includes scale factor of 1.1.

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1318.0± 1.5 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
1323 ± 4 ±3		ACCIARRI 97T	L3		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1320 ± 7		ALBRECHT 97B	ARG		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1311.3± 1.6±3.0	72400	AMELIN 96	VES		$36\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1310 ± 5		ARMSTRONG 90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
1323.8± 2.3	4022	AUGUSTIN 89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
1320.6± 3.1	3562	AUGUSTIN 89	DM2	0	$J/\psi \to \rho^0 a_2^0$
1317 ± 2	25000	[1] DAUM 80C	SPEC	−	$63,94\ \pi^- p \to 3\pi p$
1320 ±10	1097	[1] BALTAY 78B	HBC	+0	$15\ \pi^+ p \to p4\pi$
1306 ± 8		FERRERSORIA 78	OMEG	−	$9\ \pi^- p \to p3\pi$
1318 ± 7	1600	[1] EMMS 75	DBC	0	$4\ \pi^+ n \to p(3\pi)^0$
1315 ± 5		[1] ANTIPOV 73C	CNTR	−	$25,40\ \pi^- p \to p\eta\pi^-$
1306 ± 9	1580	CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1305 ±14		CONDO 93	SHF		$\gamma p \to \eta\pi^+\pi^+\pi^-$
1310 ± 2		[1] EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to 3\pi p$
1343 ±11	490	BALTAY 78B	HBC	0	$15\ \pi^+ p \to \Delta 3\pi$
1309 ± 5	5000	BINNIE 71	MMS	−	$\pi^- p$ near a_2 threshold
1299 ± 6	28000	BOWEN 71	MMS	−	$5\ \pi^- p$
1300 ± 6	24000	BOWEN 71	MMS	+	$5\ \pi^+ p$
1309 ± 4	17000	BOWEN 71	MMS	−	$7\ \pi^- p$
1306 ± 4	941	ALSTON-... 70	HBC	+	$7.0\ \pi^+ p \to 3\pi p$

[1] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.



$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1318.1± 0.7 OUR AVERAGE					
1319 ± 5	4700	[2,3] CLELAND 82B	SPEC	+	$50\ \pi^+ p \to K^0_S K^+ p$
1324 ± 6	5200	[2,3] CLELAND 82B	SPEC	−	$50\ \pi^- p \to K^0_S K^- p$
1320 ± 2	4000	CHABAUD 80	SPEC	−	$17\ \pi^- A \to K^0_S K^- A$
1312 ± 4	11000	CHABAUD 78	SPEC	−	$9.8\ \pi^- p \to K^- K^0_S p$
1316 ± 2	4730	CHABAUD 78	SPEC	−	$18.8\ \pi^- p \to K^- K^0_S p$
1318 ± 1		[2,4] MARTIN 78D	SPEC	−	$10\ \pi^- p \to K^0_S K^- p$
1320 ± 2	2724	MARGULIE 76	SPEC	−	$23\ \pi^- p \to K^- K^0_S p$
1313 ± 4	730	FOLEY 72	CNTR	−	$20.3\ \pi^- p \to K^- K^0_S p$
1319 ± 3	1500	[4] GRAYER 71	ASPK	−	$17.2\ \pi^- p \to K^- K^0_S p$

• • • We do not use the following data for averages, fits, limits, etc. • • •					
1330 ±11	1000	[2,3] CLELAND 82B	SPEC	+	30 $\pi^+ p \to K^0_S K^+ p$
1324 ± 5	350	HYAMS 78	ASPK	+	12.7 $\pi^+ p \to K^+ K^0_S p$

[2] From a fit to $J^P = 2^+$ partial wave.
[3] Number of events evaluated by us.
[4] Systematic error in mass scale subtracted.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1318.0±1.5 OUR AVERAGE					
1317 ±1 ±2		THOMPSON 97	MPS		18 $\pi^- p \to \eta\pi^- p$
1315 ±5 ±2		[5] AMSLER 94D	CBAR		0.0 $\bar{p}p \to \pi^0\pi^0\eta$
1325.1±5.1		AOYAGI 93	BKEI		$\pi^- p \to \eta\pi^- p$
1317.7±1.4±2.0		BELADIDZE 93	VES		$37\pi^- N \to \eta\pi^- N$
1323 ±8	1000	[6] KEY 73	OSPK	−	6 $\pi^- p \to p\pi^-\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1324 ±5		ARMSTRONG 93C	E760	0	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
1336.2±1.7	2561	DELFOSSE 81	SPEC	+	$\pi^\pm p \to p\pi^\pm\eta$
1330.7±2.4	1653	DELFOSSE 81	SPEC	−	$\pi^\pm p \to p\pi^\pm\eta$
1324 ±8	6200	[6,7] CONFORTO 73	OSPK	−	6 $\pi^- p \to pMM^-$

[5] The systematic error of 2 MeV corresponds to the spread of solutions.
[6] Error includes 5 MeV systematic mass-scale error.
[7] Missing mass with enriched MMS = $\eta\pi^-$, $\eta = 2\gamma$.

$\eta'\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
1327.0±10.7	BELADIDZE 93	VES	$37\pi^- N \to \eta'\pi^- N$

$a_2(1320)$ WIDTH

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
104.1± 2.0 OUR AVERAGE					
105 ±10 ±11		ACCIARRI 97T	L3		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
120 ±10		ALBRECHT 97B	ARG		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
103.0± 6.0± 3.3	72400	AMELIN 96	VES		36 $\pi^- p \to \pi^+\pi^-\pi^0 n$
120 ±10		ARMSTRONG 90	OMEG	0	300.0$pp \to pp\pi^+\pi^-\pi^0$
107.0± 9.7	4022	AUGUSTIN 89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
118.5±12.5	3562	AUGUSTIN 89	DM2	0	$J/\psi \to \rho^0 a_2^0$
97 ± 5		[8] EVANGELISTA 81	OMEG	−	12 $\pi^- p \to 3\pi p$
96 ± 9	25000	[8] DAUM 80C	SPEC	−	63,94 $\pi^- p \to 3\pi p$
110 ±15	1097	[8] BALTAY 78B	HBC	+0	15 $\pi^+ p \to p4\pi$
112 ±18	1600	[8] EMMS 75	DBC	0	4 $\pi^+ n \to p(3\pi)^0$
122 ±14	1200	[8,9] WAGNER 75	HBC	0	7 $\pi^+ p \to \Delta^{++}(3\pi)^0$
115 ±15		[8] ANTIPOV 73C	CNTR	−	25,40 $\pi^- p \to p\eta\pi^-$
99 ±15	1580	CHALOUPKA 73	HBC	−	3.9 $\pi^- p$
105 ± 5	28000	BOWEN 71	MMS	−	5 $\pi^- p$
99 ± 5	24000	BOWEN 71	MMS	+	5 $\pi^+ p$
103 ± 5	17000	BOWEN 71	MMS	−	7 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
120 ±40		CONDO 93	SHF		$\gamma p \to \eta\pi^+\pi^+\pi^-$
115 ±14	490	BALTAY 78B	HBC	0	15 $\pi^+ p \to \Delta 3\pi$
72 ±16	5000	BINNIE 71	MMS	−	$\pi^- p$ near a_2 threshold
79 ±12	941	ALSTON-... 70	HBC	+	7.0 $\pi^+ p \to 3\pi p$

[8] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.
[9] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$K^\pm K^0_S$ AND $\eta\pi$ MODES

VALUE (MeV)	DOCUMENT ID
107 ±5 OUR ESTIMATE	
110.3±1.7 OUR AVERAGE Includes data from the 2 datablocks that follow this one.	

$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
109.8± 2.4 OUR AVERAGE					
112 ±20	4700	[10,11] CLELAND 82B	SPEC	+	50 $\pi^+ p \to K^0_S K^+ p$
120 ±25	5200	[10,11] CLELAND 82B	SPEC	−	50 $\pi^- p \to K^0_S K^- p$
106 ± 4	4000	CHABAUD 80	SPEC	−	17 $\pi^- A \to K^0_S K^- A$
126 ±11	11000	CHABAUD 78	SPEC	−	9.8 $\pi^- p \to K^- K^0_S p$
101 ± 8	4730	CHABAUD 78	SPEC	−	18.8 $\pi^- p \to K^- K^0_S p$
113 ± 4		[10,12] MARTIN 78D	SPEC	−	10 $\pi^- p \to K^0_S K^- p$
105 ± 8	2724	[12] MARGULIE 76	SPEC	−	23 $\pi^- p \to K^- K^0_S p$
113 ±19	730	FOLEY 72	CNTR	−	20.3 $\pi^- p \to K^- K^0_S p$
123 ±13	1500	[12] GRAYER 71	ASPK	−	17.2 $\pi^- p \to K^- K^0_S p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
121 ±51	1000	[10,11] CLELAND 82B	SPEC	+	30 $\pi^+ p \to K^0_S K^+ p$
110 ±18	350	HYAMS 78	ASPK	+	12.7 $\pi^+ p \to K^+ K^0_S p$

[10] From a fit to $J^P = 2^+$ partial wave.
[11] Number of events evaluated by us.
[12] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
111.0± 2.5 OUR AVERAGE					
112 ± 3 ±2		[13] AMSLER 94D	CBAR		0.0 $\bar{p}p \to \pi^0\pi^0\eta$
103 ± 6 ±3		BELADIDZE 93	VES		$37\pi^- N \to \eta\pi^- N$
112.2± 5.7	2561	DELFOSSE 81	SPEC	+	$\pi^\pm p \to p\pi^\pm\eta$
116.6± 7.7	1653	DELFOSSE 81	SPEC	−	$\pi^\pm p \to p\pi^\pm\eta$
108 ± 9	1000	KEY 73	OSPK	−	6 $\pi^- p \to p\pi^-\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
127 ± 2 ±2		[14] THOMPSON 97	MPS		18 $\pi^- p \to \eta\pi^- p$
118 ±10		ARMSTRONG 93C	E760	0	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
104 ± 9	6200	[15] CONFORTO 73	OSPK	−	6 $\pi^- p \to pMM^-$

[13] The systematic error of 2 MeV corresponds to the spread of solutions.
[14] Resolution is not unfolded.
[15] Missing mass with enriched MMS = $\eta\pi^-$, $\eta = 2\gamma$.

$\eta'\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
106±32	BELADIDZE 93	VES	$37\pi^- N \to \eta'\pi^- N$

$a_2(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\rho\pi$	(70.1±2.7) %	S=1.2
Γ_2	$\eta\pi$	(14.5±1.2) %	
Γ_3	$\omega\pi\pi$	(10.6±3.2) %	S=1.3
Γ_4	$K\overline{K}$	(4.9±0.8) %	
Γ_5	$\eta'(958)\pi$	(5.3±0.9) × 10^{-3}	
Γ_6	$\pi^\pm\gamma$	(2.8±0.6) × 10^{-3}	
Γ_7	$\gamma\gamma$	(9.4±0.7) × 10^{-6}	
Γ_8	$\pi^+\pi^-\pi^-$	< 8 %	CL=90%
Γ_9	e^+e^-	< 2.3 × 10^{-7}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 18 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 9.3 for 15 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc}
x_2 & 10 & & \\
x_3 & -89 & -46 & \\
x_4 & -1 & -2 & -24 \\
\hline
 & x_1 & x_2 & x_3
\end{array}$$

$a_2(1320)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ Γ_6

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
295± 60	CIHANGIR 82	SPEC	+	200 $\pi^+ A$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
461±110	MAY 77	SPEC	±	9.7 γA

$\Gamma(\gamma\gamma)$ — Γ_7

VALUE (keV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00±0.06 OUR AVERAGE						
0.98±0.05±0.09		ACCIARRI	97T	L3		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
0.96±0.03±0.13		ALBRECHT	97B	ARG		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.26±0.26±0.18	36	BARU	90	MD1		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.00±0.07±0.15	415	BEHREND	90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.03±0.13±0.21		BUTLER	90	MRK2		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.01±0.14±0.22	85	OEST	90	JADE		$e^+e^- \to e^+e^-\pi^0\eta$
0.90±0.27±0.15	56	[16] ALTHOFF	86	TASS	0	$e^+e^- \to e^+e^-3\pi$
1.14±0.20±0.26		[17] ANTREASYAN	86	CBAL	0	$e^+e^- \to e^+e^-\pi^0\eta$
1.06±0.18±0.19		BERGER	84C	PLUT	0	$e^+e^- \to e^+e^-3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.81\pm0.19^{+0.42}_{-0.11}$	35	[16] BEHREND	83B	CELL	0	$e^+e^- \to e^+e^-3\pi$
0.77±0.18±0.27	22	[17] EDWARDS	82F	CBAL	0	$e^+e^- \to e^+e^-\pi^0\eta$

[16] From $\rho\pi$ decay mode.
[17] From $\eta\pi^0$ decay mode.

$\Gamma(e^+e^-)$ — Γ_9

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<25	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\eta$

$a_2(1320)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_4\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.126±0.007±0.028	[18] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081±0.006±0.027	[19] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^-K^+K^-$

[18] Using an incoherent background.
[19] Using a coherent background.

$a_2(1320)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\rho\pi)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.070±0.012 OUR FIT						
0.078±0.017		CHABAUD	78	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.056±0.014	50	[20] CHALOUPKA	73	HBC	−	3.9 π^-p
0.097±0.018	113	[20] ALSTON-...	71	HBC	+	7.0 π^+p
0.06 ±0.03		[20] ABRAMOVI...	70B	HBC	−	3.93 π^-p
0.054±0.022		[20] CHUNG	68	HBC	−	3.2 π^-p

[20] Included in CHABAUD 78 review.

$\Gamma(\eta\pi)/[\Gamma(\rho\pi)+\Gamma(\eta\pi)+\Gamma(K\overline{K})]$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.162±0.012 OUR FIT						
0.140±0.028 OUR AVERAGE						
0.13 ±0.04		ESPIGAT	72	HBC	±	0.0 $\overline{p}p$
0.15 ±0.04	34	BARNHAM	71	HBC	+	3.7 π^+p

$\Gamma(\eta\pi)/\Gamma(\rho\pi)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.207±0.018 OUR FIT						
0.213±0.020 OUR AVERAGE						
0.18 ±0.05		FORINO	76	HBC		11 π^-p
0.22 ±0.05	52	ANTIPOV	73	CNTR	−	40 π^-p
0.211±0.044	149	CHALOUPKA	73	HBC	−	3.9 π^-p
0.246±0.042	167	ALSTON-...	71	HBC	+	7.0 π^+p
0.25 ±0.09	15	BOECKMANN	70	HBC	+	5.0 π^+p
0.23 ±0.08	22	ASCOLI	68	HBC	−	5 π^-p
0.12 ±0.08		CHUNG	68	HBC	−	3.2 π^-p
0.22 ±0.09		CONTE	67	HBC	−	11.0 π^-p

$\Gamma(\eta'(958)\pi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.006	95	ALDE	92B	GAM2		38,100 $\pi^-p \to \eta'\pi^0n$
<0.02	97	BARNHAM	71	HBC	+	3.7 π^+p
0.004±0.004		BOESEBECK	68	HBC	+	8 π^+p

$\Gamma(\eta'(958)\pi)/\Gamma(\rho\pi)$ — Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.011	90	EISENSTEIN	73	HBC	−	5 π^-p
<0.04		ALSTON-...	71	HBC	+	7.0 π^+p
$0.04^{+0.03}_{-0.04}$		BOECKMANN	70	HBC	0	5.0 π^+p

$\Gamma(K\overline{K})/[\Gamma(\rho\pi)+\Gamma(\eta\pi)+\Gamma(K\overline{K})]$ — $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.054±0.009 OUR FIT						
0.048±0.012 OUR AVERAGE						
0.05 ±0.02		TOET	73	HBC	+	5 π^+p
0.09 ±0.04		TOET	73	HBC	0	5 π^+p
0.03 ±0.02	8	DAMERI	72	HBC	−	11 π^-p
0.06 ±0.03	17	BARNHAM	71	HBC	+	3.7 π^+p
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.020±0.004		[21] ESPIGAT	72	HBC	±	0.0 $\overline{p}p$

[21] Not averaged because of discrepancy between masses from $K\overline{K}$ and $\rho\pi$ modes.

$\Gamma(\pi^+\pi^-\pi^-)/\Gamma(\rho\pi)$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.12	90	ABRAMOVI...	70B	HBC	−	3.93 π^-p

$\Gamma(\pi^\pm\gamma)/\Gamma_{\text{total}}$ — Γ_6/Γ

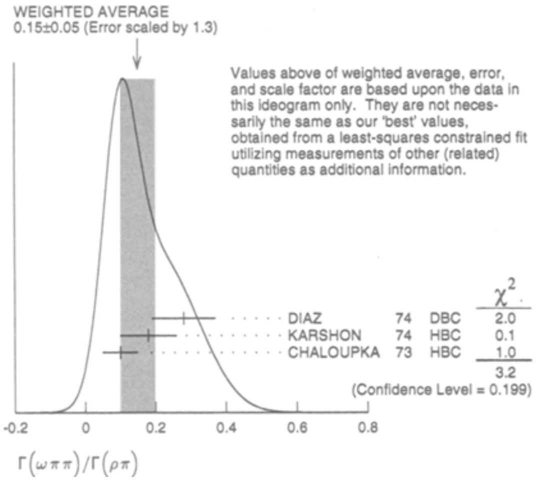
VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.005^{+0.005}_{-0.003}$	[22] EISENBERG	72	HBC	4.3,5.25,7.5 γp

[22] Pion-exchange model used in this estimation.

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.15±0.05 OUR FIT Error includes scale factor of 1.3.						
0.15±0.05 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.						
0.28±0.09	60	DIAZ	74	DBC	0	6 π^+n
0.18±0.08		[23] KARSHON	74	HBC		Avg. of above two
0.10±0.05	279	CHALOUPKA	73	HBC	−	3.9 π^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.29±0.08	140	[23] KARSHON	74	HBC	0	4.9 π^+p
0.10±0.04	60	[23] KARSHON	74	HBC	+	4.9 π^+p
0.19±0.08		DEFOIX	73	HBC	0	0.7 $\overline{p}p$

[23] KARSHON 74 suggest an additional $I = 0$ state strongly coupled to $\omega\pi\pi$ which could explain discrepancies in branching ratios and masses. We use a central value and a systematic spread.



$\Gamma(\eta'(958)\pi)/\Gamma(\eta\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.037±0.006 OUR AVERAGE				
0.032±0.009	ABELE	97C	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\eta'$
0.047±0.010±0.004	[24] BELADIDZE	93	VES	$37\pi^-N \to a_2^-N$
0.034±0.008±0.005	BELADIDZE	92	VES	$36\pi^-\text{C} \to a_2^-\text{C}$

[24] Using $B(\eta' \to \pi^+\pi^-\eta) = 0.441$, $B(\eta \to \gamma\gamma) = 0.389$ and $B(\eta \to \pi^+\pi^-\pi^0) = 0.236$.

$a_2(1320)$ REFERENCES

ABELE 97C PL B404 179 A. Abele, Adomeit, Amsler+ (Crystal Barrel Collab.)
ACCIARRI 97T PL B413 147 M. Acciarri+
ALBRECHT 97B ZPHY C74 469 +Hamacher, Hofmann+ (ARGUS Collab.)
THOMPSON 97 PRL 79 1630 +Adams+ (E852 Collab.)
AMELIN 96 ZPHY C70 71 +Berdnikov, Bityukov+ (SERP, TBIL)
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
AOYAGI 93 PL B314 246 +Fukui, Hasegawa+ (BKEI Collab.)
ARMSTRONG 93C PL B307 394 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
BELADIDZE 93 PL 313 276 +Berdnikov, Bityukov+ (VES Collab.)
CONDO 93 PR D48 3045 +Handler, Bugg+ (SLAC Hybrid Collab.)
ALDE 92B ZPHY C54 549 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)
BELADIDZE 92 ZPHY C54 235 +Bityukov, Borisov+ (VES Collab.)
ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
ARMSTRONG 90 ZPHY C48 213 +Benayoun, Beusch (WA76 Collab.)
BARU 90 ZPHY C48 581 +Blinov, Blinov+ (MD-1 Collab.)
BEHREND 90C ZPHY C46 583 +Criegee+ (CELLO Collab.)
BUTLER 90 PR D42 1368 +Boyer+ (Mark II Collab.)
OEST 90 ZPHY C47 343 +Olsson+ (JADE Collab.)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
ALTHOFF 86 ZPHY C31 537 +Boch, Foster, Bernardi+ (TASSO Collab.)
ANTREASYAN 86 PR D33 1847 +Aschman, Besset, Bienlein+ (Crystal Ball Collab.)
BERGER 84C PL 149B 427 +Klovning, Burger+ (PLUTO Collab.)
BEHREND 83B PL 125B 518 +D'Agostini+ (CELLO Collab.)
CIHANGIR 82 PL 117B 123 +Berg, Biel, Chandlee+ (FNAL, MINN, ROCH)
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
EDWARDS 82F PL 110B 82 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
DELFOSSE 81 NP B183 349 +Guisan, Martin, Muhlemann, Weill+ (GEVA, LAUS)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
CHABAUD 80 NP B175 189 +Hyams, Papadopoulou+ (CERN, MPIM, AMST)
DAUM 80C PL 89B 276 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
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MAY 77 PR D16 1983 +Abramson, Andrews, Busnello+ (ROCH, CORN)
FORINO 76 NC 35A 465 +Gessaroli+ (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
MARGULIE 76 PR D14 667 +Kramer, Foley, Love, Lindenbaum+ (BNL, CUNY)
EMMS 75 PL 58B 117 +Jones, Kinson, Stacey, Bell+ (BIRM, DURH, RHEL) JP
WAGNER 75 PL 58B 201 +Tabak, Chew (LBL) JP
DIAZ 74 PRL 32 260 +Dibianca, Fickinger, Anderson+ (CASE, CMU)
KARSHON 74 PRL 32 852 +Mikenberg, Pitluck, Eisenberg, Ronat+ (REHO)
ANTIPOV 73 NP B63 175 +Ascoli, Busnello, Focacci+ (CERN, SERP) JP
ANTIPOV 73C NP B63 153 +Ascoli, Busnello, Focacci+ (CERN, SERP) JP
CHALOUPKA 73 PL 44B 211 +Dobrzynski, Ferrando, Losty+ (CERN)
CONFORTO 73 PL 45B 154 +Mobley, Key+ (EFI, FNAL, TNTO, WISC)
DEFOIX 73 PL 43B 141 +Dobrzynski, Espigat, Nascimento+ (CDEF)
EISENSTEIN 73 PR D7 278 +Schultz, Ascoli, Ioffredo+ (ILL)
KEY 73 PRL 30 503 +Conforto, Mobley+ (TNTO, EFI, FNAL, WISC)
TOET 73 NP B63 248 +Thuan, Major+ (NIJM, BONN, DURH, TORI)
DAMERI 72 NC 9A 1 +Borzatta, Goussu+ (GENO, MILA, SACL)
EISENBERG 72 PR D5 15 +Ballam, Dagan+ (REHO, SLAC, TELA)
ESPIGAT 72 NP B36 93 +Ghesquiere, Lillestol, Montanet (CERN, CDEF)
FOLEY 72 PR D6 747 +Love, Ozaki, Platner, Lindenbaum+ (BNL, CUNY)
ALSTON-... 71 PL 34B 156 Alston-Garnjost, Barbaro, Buhl, Derenzo+ (LRL)
BARNHAM 71 PRL 26 1494 +Abrams, Butler, Coyne, Goldhaber, Hall+ (LBL)
BINNIE 71 PL 36B 257 +Camilleri, Duane, Faruqi, Burton+ (LOIC, SHMP)
BOWEN 71 PRL 26 1663 +Earles, Faissler, Blieden+ (NEAS, STON)
GRAYER 71 PL 34B 333 +Hyams, Jones, Schlein, Blum+ (CERN, MPIM)
ABRAMOVI... 70B NP B23 466 Abramovich, Blumenfeld, Bruyant+ (CERN) JP
ALSTON-... 70 PL 33B 607 Alston-Garnjost, Barbaro, Buhl, Derenzo+ (LRL)
BOECKMANN 70 NP B16 221 +Major+ (BONN, DURH, NIJM, EPOL, TORI)
ASCOLI 68 PRL 20 1321 +Crawley, Mortara, Shapiro, Bridges+ (ILL) JP
BOESEBECK 68 NP B4 501 +Deutschmann+ (AACH, BERL, CERN)
CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
CONTE 67 NC 51A 175 +Tomasini, Cords+ (GENO, HAMB, MILA, SACL)

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JENNI 83 PR D27 1031 +Burke, Telnov, Abrams, Blocker+ (SLAC, LBL)
BEHREND 82C PL 114B 378 +Chen, Fenner, Field+ (CELLO Collab.)
ADERHOLZ 65 PR 138B 897 (AACH3, BERL, BIRM, BONN, HAMB, LOIC, MPIM)
ALITTI 65 PL 15 69 +Baton, Deler, Crussard+ (SACL, BGNA) JP
CHUNG 65 PRL 15 325 +Dahl, Hardy, Hess, Jacobs, Kirz (LRL)
FORINO 65B PL 19 68 +Gessaroli+ (BGNA, BARI, FIRZ, ORSAY, SACL)
LEFEBVRES 65 PL 19 434 +Levrat+ (CERN Missing Mass Spect. Collab.)
SEIDLITZ 65 PRL 15 217 +Dahl, Miller (LRL)
ADERHOLZ 64 PL 10 226 + (AACH3, BERL, BIRM, BONN, DESY, HAMB+)
CHUNG 64 PRL 12 621 +Dahl, Hardy, Hess, Kalbfleisch, Kirz (LRL)
GOLDHABER 64 PRL 12 336 +Brown, Kadyk, Shen+ (LRL, UCB)
LANDER 64 PRL 13 346A +Abolins, Carmony, Hendricks, Xuong+ (UCSD)

$f_0(1370)$

$I^G(J^{PC}) = 0^+(0^{++})$

NOTE ON SCALAR MESONS

Written March 1998 by S. Spanier (Zürich) and N. Törnqvist (Helsinki).

In contrast to the vector and tensor mesons the identification of the scalar mesons is a long standing puzzle. The problem originates from their large decay widths causing a strong overlap of individual resonances within the same partial wave, and at the same time several decay channels open up within a short mass interval. In addition the $K\overline{K}$ and $\eta\eta$ thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$q\overline{q}$ scalar objects like glueballs and multiquark states in the mass range below 1800 MeV. In spite of these problems the understanding of the scalars has improved considerably during the last few years, because we now have high statistics measurements of different production modes from: $p\overline{p}$ annihilation at rest, πN-scattering on polarized/unpolarized targets, central production, $J/\psi(1S)$ decays, D-meson decays, $\gamma\gamma$-formation. Furthermore, we have had a strong development of better theoretical models for the reaction amplitudes, which are based on common fundamental principles. These allow direct comparison and interpretation of many different experimental results. Two-body unitarity, analyticity, Lorentz invariance, chiral- and flavor-symmetry constraints have been implemented into the transition amplitudes using different general methods (K-matrix formalism, N/D-method, Dalitz-Tuan ansatz, unitarized quark models with coupled channels, *etc.*). In general, mass and width parameters of a resonance are found from the position of the nearest pole in the T-matrix (or equivalently the S-matrix) at an unphysical sheet of the complex energy plane: $(E - i\frac{\Gamma}{2})$. It is important to realize, that only in the case of well separated resonances, far away from the opening of decay channels, does a naive Breit-Wigner parametrization (or K-matrix pole parametrization) agree approximately with the T-matrix pole position in the amplitude. Breit-Wigner parameters are sensitive to background, nearby thresholds *etc.*, while T-matrix poles depend only on the limitations of the theoretical model.

In this note we discuss all light scalars organized in the listings under the entries ($I = 1/2$) $K_0^*(1430)$, ($I = 1$) $a_0(980)$, $a_0(1450)$, and ($I = 0$) σ or $f_0(400–1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1500)$. The list is minimal and does not necessarily exhaust the list of actual resonances.

The $I = 1/2$ states

The $K_0^*(1430)$ (ASTON 88) is the least controversial of the light scalar mesons. The phase shift rises smoothly from threshold, passes 90° at 1350 MeV, and then continues to rise to about 170° at 1600 MeV at the first important inelastic threshold $K\eta'(958)$. Thus it behaves like a single broad, nearly elastic resonance. ABELE 98 finds for the T-matrix pole parameters, $m \approx 1430$ MeV and $\Gamma \approx 290$ MeV, while the K-matrix pole of the same data is at about 1340 MeV using $K\overline{K}\pi$ in $p\overline{p}$ annihilation at rest. This agrees with the LASS (ASTON 88) determination. The scattering length near threshold is $a = 2.56 \pm 0.20$ (GeV/c)$^{-1}$ (ABELE 98).

The $I = 1$ states

Two states are established, the well-known $a_0(980)$, and the $a_0(1450)$ found by Crystal Barrel (AMSLER 94D). Independently of any model about the nature of the $a_0(980)$ the $K\overline{K}$ component in the wave function of the state must be large: the $a_0(980)$ lies very close to the opening of the $K\overline{K}$ channel to which it couples strongly. This gives an important cusp-like behaviour in the resonant amplitude. Hence, its mass and width parameters are strongly distorted. To reveal its true coupling constants a coupled channel model with energy-dependent widths and mass shift contributions must be applied. A naive Breit-Wigner form is certainly inadequate.

The relative coupling $K\overline{K}/\pi\eta$ in previous editions was determined only indirectly from $f_1(1285)$ (CORDEN 78, DEFOIX 72) or $\eta(1410)$ decays (BAI 90C, BOLTON 92B, AMSLER 95F) or from the line shape observed in the $\pi\eta$ decay mode (FLATTE 76, AMSLER 94D, BUGG 94, JANSSEN 95). From analysis of $\pi\pi\eta$ and $K\overline{K}\pi$ final states of $\overline{p}p$ annihilation at rest a relative production ratio $\mathrm{B}(\overline{p}p \rightarrow \pi a_0; a_0 \rightarrow K\overline{K})/\mathrm{B}(\overline{p}p \rightarrow \pi a_0; a_0 \rightarrow \pi\eta) = 0.23 \pm 0.05$ is obtained by ABELE 98. Tuning of the couplings in a coupled channel formula to reproduce the production ratio for the integrated mass distributions gives a relative branching ratio $\Gamma(K\overline{K})/\Gamma(\pi\eta)$=1.03 ± 0.14. Analysis of $p\overline{p}$ annihilation data also found that the width determined from the T-matrix pole is 92 ± 8 MeV, while the observed width of the peak in the $\pi\eta$ mass spectrum is about 45 MeV.

In our table the mass position comes out very consistently near 980 MeV in all measurements, but the width takes values between 50 and 300 MeV, because of the differences in the models used in the analyses. Using the relative production ratio and the observed 2-photon generation of $a_0(980)$ one can calculate the 2-photon width of $a_0(980)$ to be $\Gamma_{\gamma\gamma} = (0.30 \pm 0.10)$ keV, which is similar to that of $f_0(980)$.

The $a_0(1450)$ is seen by the Crystal Barrel experiment in its $\pi\eta$, $K\overline{K}$, and $\pi\eta'(958)$ decay modes. The relative couplings to the different final states are found to be close to SU(3)-flavor predictions for an ordinary $q\overline{q}$ meson.

The $I=0$ states

The $I = 0$ $J^{PC} = 0^{++}$ sector is the most complex one both experimentally and theoretically. The data have been obtained from $\pi\pi$, $K\overline{K}$, $\eta\eta$, 4π, and $\eta\eta'(958)$ systems produced in S-waves by nonstrange initial states. From the high statistics data sets collected from $\overline{p}p$ annihilation at rest into $\pi^0 f_0$'s, where the f_0 decay into the above mentioned channels, one concludes that at least four poles are needed in the mass range from $\pi\pi$ threshold to about 1600 MeV. The claimed isoscalar resonances are found under the separate entries σ or $f_0(400\text{–}1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1500)$.

Below 1100 MeV the important data come from $\pi\pi$ and $K\overline{K}$ final states. Information on the $\pi\pi$ S-wave phase shift $\delta^I_J = \delta^0_0$ was extracted already 20 years ago from πN scattering with unpolarized (GRAYER 74) and polarized target (BECKER 79) and near threshold from K_{e4}-decay (ROSSELET 77). The $\pi\pi$ S-wave inelasticity is not accurately known, and the reported $\pi\pi \rightarrow K\overline{K}$ cross sections (WETZEL 76, POLYCHRONAKOS 79, COHEN 80, ETKIN 82B) may have large uncertainties. Recently, the πN data (GRAYER 74, BECKER 79) have been reevaluated in a combined partial-wave analysis (KAMINSKI 97). Out of four, two relevant solutions are found with the S-wave phase-shift rising slower than the P-wave [$\rho(770)$], which is used as reference. One of these corresponds to the well known "down" solution of (GRAYER 74), the other "up" solution shows a decrease of the modulus in the mass interval 800-980 MeV. Both solutions exhibit at 1 GeV a sudden drop in the modulus and in the inelasticity parameter η^0_0, which is due to the appearance of $f_0(980)$ very close to the opening of the $K\overline{K}$-threshold. The phase shift δ^0_0 rises smoothly up to this point where it jumps by 120° (in the "up") or 140° (in the "down"-solution) to reach 230°, from which point both continue to rise slowly.

SVEC 97 using data on πN(polarized) producing the $\pi\pi$ system from 600 to 900 MeV suggests that there exists a narrow state at 750 MeV with a small width of 100 to 200 MeV. Such a solution is also found by (KAMINSKI 97) using the CERN-Munich(-Cracow) data considering both π- and $a_1(1260)$-exchange in the reaction amplitudes. However, they show that unitarity is violated for this solution; therefore a narrow light f_0 state below 900 MeV seems to be excluded. Also, the $2\pi^0$ invariant mass spectra of $p\overline{p}$ annihilation at rest (AMSLER 95B, ABELE 96) and central collision (ALDE 97) do not show a narrow resonance below 900 MeV, and these data are consistently described with the standard "down" solution (GRAYER 74, KAMINSKI 97), which allows for the existence of the broad ($\Gamma \approx 500$ MeV) σ listed under $f_0(400\text{–}1200)$.

For low-energy $\pi\pi$ scattering the predicted Weinberg scattering length for the isoscalar S-wave a^0_0 is 0.16, chiral perturbation theory including one-loop corrections increases this value to $a^0_0 \approx 0.20$ while the slope parameter is $b^0_0 \approx 0.18$ (GASSER 83, RIGGENBACH 91). With two-loop corrections one still gets a little larger value $a^0_0 = 0.217$ (BIJNENS 96), but electromagnetic corrections reduce this value to 0.208 (MALTMAN 97). Experimentally the region near the $\pi\pi$ threshold is difficult to investigate. Current values of these quantities are $a^0_0 = 0.26 \pm 0.05$ and $b^0_0 = 0.25 \pm 0.03$ (NAGELS 79).

An experimentally very well studied meson resonance is the $f_0(1500)$ seen by the Crystal Barrel experiment in five decay modes: $\pi\pi$, $K\overline{K}$, $\eta\eta$, $\eta\eta'(958)$, and 4π (AMSLER 95D, ABELE 96, ABELE 98). Due to its interference with the $f_0(1370)$ the peak attributed to $f_0(1500)$ can appear shifted in mass to 1590 MeV, where it was observed by the GAMS collaboration (BINON 83) in the $\eta\eta$ mass spectrum. They applied a sum of Breit-Wigner functions for the dynamics in the resonant amplitude. In central production (ANTINORI 95) a peak at 1450 MeV having a width of 60 MeV can be interpreted as the coherent sum of $f_0(1370)$ and $f_0(1500)$. The $\overline{p}p$ and $\overline{n}p/\overline{p}n$ reactions show a single enhancement at 1400 MeV in the invariant 4π mass (GASPERO 93, ADAMO 93, AMSLER 94, ABELE 96). In the $5\pi^0$ channel (ABELE 96) this structure was resolved into $f_0(1500)$ and $f_0(1370)$, found at a somewhat lower mass around 1300 MeV. An additional scalar in mass above 1700 MeV had to be introduced in the re-analysis of the reaction $J/\psi(1S) \rightarrow \gamma 4\pi$ (BUGG 95). According to these investigations the $f_0(1500)$ decay proceeds dominantly via $\sigma\sigma \rightarrow 4\pi$ where σ denotes the $\pi\pi$ S-wave below $K\overline{K}$ threshold. The $K\overline{K}$ decay of $f_0(1500)$ is suppressed (ABELE 98).

The determination of the $\pi\pi$ coupling of $f_0(1370)$ is inhibited by the strong overlap with the broad background from the $f_0(400\text{–}1200)$. Since it does not show up prominently in the 2π spectra its mass and width are difficult to fix. A resonance band in the $\pi^0\eta\eta$ final state of $p\overline{p}$ annihilation at rest (AMSLER 95D) is attributed to it. Data on $\pi\pi \rightarrow K\overline{K}$ show an enhancement at around 1300 MeV in the scalar partial wave (WETZEL 76, COHEN 80, POLYCHRONAKOS 79, COSTA 80, LONGACRE 86). According to the phase shift the resonance is found around 1400 MeV (COHEN 80), while a recent re-analysis (BUGG 96) claims a trend to lower mass. Further information about the $K\overline{K}$ decay of the scalars are most welcome, in particular those which clearly distinguish between the $I = 0$ and the $I = 1$ system.

In the analysis of (ANISOVICH 97, 97C) using data of πN and $\overline{p}p$ annihilation reactions a fifth pole at 1530 MeV about 1 GeV off the physical region is added.

Interpretation

Almost every model on the scalar states agrees that the $K_0^*(1430)$ is the $1\ ^3P_0$ quark model $s\overline{u}$ or $s\overline{d}$ state, but the other scalars remain controversial.

The $f_0(980)$ and $a_0(980)$ are often interpreted as being multiquark states (JAFFE 77) or $K\overline{K}$ bound states (WEINSTEIN 90). This picture is supported by their 2-photon widths which are smaller than expected for $q\overline{q}$ mesons, if one neglects the $K\overline{K}$ component. Using a simple quark model one is led to put the $f_0(1370)$, $a_0(1450)$, and $K_0^*(1430)$ into the same SU(3) flavor nonet being the $(u\overline{u}+d\overline{d})$, $u\overline{d}$ and the $u\overline{s}$ state, respectively. In this picture the $s\overline{s}$ state is missing experimentally. Compared with these states the $f_0(1500)$ is too narrow to be the isoscalar partner, and too light to be the first radial excitation. A non-$q\overline{q}$ (gluonium) interpretation seems likely (CLOSE 97B). See our Note on Non-$q\overline{q}$ states. As to the light $f_0(400\text{–}1200)$ structure it is far from the physical region and its interpretation in terms of a $q\overline{q}$ state or cross channel effect remains open. Such a state is often referred to as the σ or $f_0(500)$ meson.

More detailed models exist, which include more theoretical input at least phenomenologically. One such unitarized quark model with coupled channels can understand 6 of the light scalars as different unitarized manifestations of bare quarks model $^3P_0$ $q\overline{q}$ states (TORNQVIST 82, 95, 96). The σ, $f_0(980)$, $f_0(1370)$, $a_0(980)$, $a_0(1450)$, and $K_0^*(1430)$ are described as unitarized remnants of strongly shifted and mixed $q\overline{q}$ $1\ ^3P_0$ states using 6 parameters. Here the σ is the $(u\overline{u}+d\overline{d})$ state and at the same time also the chiral partner of the π. The $f_0(980)$ and $f_0(1370)$ as well as $a_0(980)$ and $a_0(1450)$ are two manifestations of the same $q\overline{q}$ state. The interpretation of $f_0(1500)$ in this scheme is an open question; it can be a glueball or a deuteron-like $\rho\rho+\omega\omega$ bound state. For other models and more details discussing the light scalar resonances see also (AU 87, MORGAN 93, ZOU 94B, JANSSEN 95, CLOSE 92, ANISOVICH 97, 97B, 97C, 97D, BEVEREN 86, KAMINSKI 94, 97B, OLLER 97, ISHIDA 96).

$f_0(1370)$ T-MATRIX POLE POSITION

Note that $\Gamma \approx 2\,\mathrm{Im}(\sqrt{s_{\text{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(1200–1500)$-i$(150–250) OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$(1290 \pm 15)-i(145 \pm 15)$	BARBERIS 97B	OMEG	450 $pp \rightarrow pp2(\pi^+\pi^-)$
$(1548 \pm 40)-i(560 \pm 40)$	BERTIN 97C	OBLX	0.0 $\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
$(1380 \pm 40)-i(180 \pm 25)$	ABELE 96B	CBAR	0.0 $\overline{p}p \rightarrow \pi^0 K_L^0 K_L^0$
$(1300 \pm 15)-i(115 \pm 8)$	BUGG 96	RVUE	
$(1330 \pm 50)-i(150 \pm 40)$	[1] AMSLER 95B	CBAR	$\overline{p}p \rightarrow 3\pi^0$
$(1360 \pm 35)-i(150\text{–}300)$	[1] AMSLER 95C	CBAR	$\overline{p}p \rightarrow \pi^0\eta\eta$
$(1390 \pm 30)-i(190 \pm 40)$	[2] AMSLER 95D	CBAR	$\overline{p}p \rightarrow 3\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
$1346 - i249$	[3,4] JANSSEN 95	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$1214 - i168$	[4,5] TORNQVIST 95	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
$1364 - i139$	AMSLER 94D	CBAR	$\overline{p}p \rightarrow \pi^0\pi^0\eta$
$(1365^{+20}_{-55})-i(134 \pm 35)$	ANISOVICH 94	CBAR	$\overline{p}p \rightarrow 3\pi^0, \pi^0\eta\eta$
$(1340 \pm 40)-i(127^{+30}_{-20})$	[6] BUGG 94	RVUE	$\overline{p}p \rightarrow 3\pi^0, \eta\eta\pi^0, \eta\pi^0\pi^0$
$1515 - i214$	[4,7] ZOU 93	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$1420 - i220$	[8] AU 87	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$

[1] Supersedes ANISOVICH 94.

[2] Coupled-channel analysis of $\overline{p}p \rightarrow 3\pi^0$, $\pi^0\eta\eta$, and $\pi^0\pi^0\eta$ on sheet IV. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.

[3] Analysis of data from FALVARD 88.

[4] The pole is on Sheet III. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.

[5] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

[6] Reanalysis of ANISOVICH 94 data.

[7] Analysis of data from OCHS 73, GRAYER 74, and ROSSELET 77.

[8] Analysis of data from OCHS 73,GRAYER 74, BECKER 79, and CASON 83.

$f_0(1370)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETER

VALUE (MeV)	*DOCUMENT ID*
1200 to 1500 OUR ESTIMATE	

$\pi\pi$ MODE

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1280±55	BERTIN 98	OBLX	50–405 $\overline{n}p \rightarrow \pi^+\pi^+\pi^-$
1186	[9] TORNQVIST 95	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
1430± 5	KAMINSKI 94	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
1472±12	ARMSTRONG 91	OMEG	300 $pp \rightarrow pp\pi\pi, ppK\overline{K}$
1275±20	BREAKSTONE 90	SFM	62 $pp \rightarrow pp\pi^+\pi^-$
1420±20	AKESSON 86	SPEC	63 $pp \rightarrow pp\pi^+\pi^-$
1256	FROGGATT 77	RVUE	$\pi^+\pi^-$ channel

[9] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

$K\overline{K}$ MODE

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1440±50	BOLONKIN 88	SPEC	40 $\pi^-p \rightarrow K_S^0K_S^0n$
1463± 9	ETKIN 82B	MPS	23 $\pi^-p \rightarrow n2K_S^0$
1425±15	WICKLUND 80	SPEC	6 $\pi N \rightarrow K^+K^-N$
~ 1300	POLYCHRO... 79	STRC	7 $\pi^-p \rightarrow n2K_S^0$

4π MODE $2(\pi\pi)_S+\rho\rho$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1374±38	AMSLER 94	CBAR	0.0 $\overline{p}p \rightarrow \pi^+\pi^-3\pi^0$
1345±12	ADAMO 93	OBLX	$\overline{n}p \rightarrow 3\pi^+2\pi^-$
1386±30	GASPERO 93	DBC	0.0 $\overline{p}n \rightarrow 2\pi^+3\pi^-$

$\eta\eta$ MODE

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1430	AMSLER 92	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\eta\eta$
1220±40	ALDE 86D	GAM4	100 $\pi^-p \rightarrow n2\eta$

$f_0(1370)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID
200 to 800 OUR ESTIMATE	

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
323 ± 13	BERTIN 98	OBLX	50–405 $\overline{n}p \to \pi^+\pi^+\pi^-$
350	[10] TORNQVIST 95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
145 ± 25	KAMINSKI 94	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
195 ± 33	ARMSTRONG 91	OMEG	300 $pp \to pp\pi\pi, ppK\overline{K}$
285 ± 60	BREAKSTONE 90	SFM	62 $pp \to pp\pi^+\pi^-$
460 ± 50	AKESSON 86	SPEC	63 $pp \to pp\pi^+\pi^-$
~ 400	[11] FROGGATT 77	RVUE	$\pi^+\pi^-$ channel

[10] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

[11] Width defined as distance between 45 and 135° phase shift.

$K\overline{K}$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$250\pm\ 80$	BOLONKIN 88	SPEC	40 $\pi^- p \to K^0_S K^0_S n$
$118^{+138}_{-\ 16}$	ETKIN 82B	MPS	23 $\pi^- p \to n2K^0_S$
$160\pm\ 30$	WICKLUND 80	SPEC	6 $\pi N \to K^+ K^- N$
~ 150	POLYCHRO... 79	STRC	7 $\pi^- p \to n2K^0_S$

4π MODE $2(\pi\pi)_S+\rho\rho$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
375 ± 61	AMSLER 94	CBAR	0.0 $\overline{p}p \to \pi^+\pi^-3\pi^0$
398 ± 26	ADAMO 93	OBLX	$\overline{n}p \to 3\pi^+2\pi^-$
310 ± 50	GASPERO 93	DBC	0.0 $\overline{p}n \to 2\pi^+3\pi^-$

$\eta\eta$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
250	AMSLER 92	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta$
320 ± 40	ALDE 86D	GAM4	100 $\pi^- p \to n2\eta$

$f_0(1370)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	4π	seen
Γ_3	$4\pi^0$	seen
Γ_4	$2\pi^+2\pi^-$	seen
Γ_5	$\pi^+\pi^-2\pi^0$	seen
Γ_6	$\rho\rho$	
Γ_7	$2(\pi\pi)_S$-wave	seen
Γ_8	$\eta\eta$	seen
Γ_9	$K\overline{K}$	seen
Γ_{10}	$\gamma\gamma$	seen
Γ_{11}	e^+e^-	not seen

$f_0(1370)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_{10}

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.4 ± 2.3	MORGAN 90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$

$\Gamma(e^+e^-)$ Γ_{11}

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<20	90	VOROBYEV 88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(1370)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.26 ± 0.09	BUGG 96	RVUE	
<0.15	[12] AMSLER 94	CBAR	$\overline{p}p \to \pi^+\pi^-3\pi^0$
<0.20	GASPERO 93	DBC	0.0 $\overline{p}n \to$ hadrons

[12] Using AMSLER 95B ($3\pi^0$).

$\Gamma(4\pi)/\Gamma_{\text{total}}$ $\Gamma_2/\Gamma = (\Gamma_3+\Gamma_4+\Gamma_5)/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.80 ± 0.04	GASPERO 93	DBC	0.0 $\overline{p}n \to$ hadrons

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	ABELE 96	CBAR	0.0 $\overline{p}p \to 5\pi^0$

$\Gamma(2\pi^+2\pi^-)/\Gamma(4\pi)$ $\Gamma_4/\Gamma_2 = \Gamma_4/(\Gamma_3+\Gamma_4+\Gamma_5)$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.420 ± 0.014	[13] GASPERO 93	DBC	0.0 $\overline{p}n \to 2\pi^+3\pi^-$

[13] Model-dependent evaluation.

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(4\pi)$ $\Gamma_5/\Gamma_2 = \Gamma_5/(\Gamma_3+\Gamma_4+\Gamma_5)$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.512 ± 0.019	[14] GASPERO 93	DBC	0.0 $\overline{p}n \to$ hadrons

[14] Model-dependent evaluation.

$\Gamma(\rho\rho)/\Gamma(2(\pi\pi)_S\text{-wave})$ Γ_6/Γ_7

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.6\ \pm0.2$	AMSLER 94	CBAR	$\overline{p}p \to \pi^+\pi^-3\pi^0$
0.58 ± 0.16	GASPERO 93	DBC	0.0 $\overline{p}n \to 2\pi^+3\pi^-$

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
0.35 ± 0.13	BUGG 96	RVUE

$f_0(1370)$ REFERENCES

BERTIN	98	PR D57 55	A. Bertin, Bruschi, Capponi+	(OBELIX Collab.)
BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)
BERTIN	97C	PL B408 476	A. Bertin, Bruschi+	(OBELIX Collab.)
ABELE	96	PL B380 453	+Adomeit, Amsler+	(Crystal Barrel Collab.)
ABELE	96B	PL B385 425	+Adomeit, Amsler+	(Crystal Barrel Collab.)
BUGG	96	NP B471 59	+Sarantsev, Zou	(LOQM, PNPI)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
TORNQVIST	95	ZPHY C68 647		(HELS)
AMSLER	94	PL B322 431	+Armstrong, Meyer+	(Crystal Barrel Collab.) JPC
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	94	PL B323 233	+Armstrong+	(Crystal Barrel Collab.) JPC
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
KAMINSKI	94	PR D50 3145	R. Kaminski+	(CRAC, IPN)
ADAMO	93	NP A558 13C	+Agnello+	(OBELIX Collab.) JPC
GASPERO	93	NP A562 407		(ROMAI) JPC
ZOU	93	PR D48 R3948	+Bugg	(LOQM)
AMSLER	92	PL B291 347	+Augustin, Baker+	(Crystal Barrel Collab.)
ARMSTRONG	91	ZPHY C51 351	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEIDH, WARS)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
WICKLUND	80	PRL 45 1469	+Ayres, Cohen, Diebold, Pawlicki	(ANL)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
FROGGATT	77	NP B129 89	+Petersen	(GLAS, NORD)
ROSSELET	77	PR D15 574	+Extermann, Fischer, Guisan+	(GEVA, SACL)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
OCHS	73	Thesis		(MPIM, MUNI)
BEIER	72B	PRL 29 511	+Buchholtz, Mann+	(PENN)

OTHER RELATED PAPERS

ANISOVICH	97	PL B395 123	+Sarantsev	(PNPI)
ANISOVICH	97B	ZPHY A357 123	A.V. Anisovich+	(FNPI)
ANISOVICH	97C	PL B413 137		
ANISOVICH	97E	PAN 60 1892 Translated from YAF 60 2065.	A.V. Anisovich+	(PNPI)
PROKOSHKIN	97	SPD 42 117 Translated from DANS 353 323.	+Kondashov, Sadovsky+	(SERP)
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
GASPERO	95	NP A588 861		(ROMA)
LI	91	PR D43 2161	+Close, Barnes+	(TENN)
BIZZARRI	69	NP B14 169	+Foster, Gavillet, Montanet+	(CERN, CDEF)
BETTINI	66	NC 42A 695	+Cresti, Limentani, Bertanza, Bigi+	(PADO, PISA)

$h_1(1380)$

$I^G(J^{PC}) = ?^-(1^{+-})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\overline{K}\pi$ system. Needs confirmation.

$h_1(1380)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1386±19 OUR AVERAGE				
1440±60	ABELE	97H	CBAR	$\overline{p}p \rightarrow K_L^0 K_S^0 \pi^0 \pi^0$
1380±20	ASTON	88C	LASS	11 $K^- p \rightarrow K_S^0 K^\pm \pi^\mp \Lambda$

$h_1(1380)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
91±30 OUR AVERAGE	Error includes scale factor of 1.1.			
170±80	ABELE	97H	CBAR	$\overline{p}p \rightarrow K_L^0 K_S^0 \pi^0 \pi^0$
80±30	ASTON	88C	LASS	11 $K^- p \rightarrow K_S^0 K^\pm \pi^\mp \Lambda$

$h_1(1380)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}^*(892)$ + *c.c.*

$h_1(1380)$ REFERENCES

ABELE	97H	PL B415 280	A. Abele+	(Crystal Barrel Collab.)
ASTON	88C	PL B201 573	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)

$\hat{\rho}(1405)$

$I^G(J^{PC}) = 1^-(1^{-+})$

OMITTED FROM SUMMARY TABLE

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\hat{\rho}(1405)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$1392\ ^{+25}_{-22}$ OUR AVERAGE					
1400 ±20 ±20	ABELE	98B	CBAR		0.0 $\overline{p}n \rightarrow \pi^- \pi^0 \eta$
$1370 \pm 16\ ^{+50}_{-30}$	[1] THOMPSON	97	MPS		18 $\pi^- p \rightarrow \eta \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1323.1± 4.6	[2] AOYAGI	93	BKEI		$\pi^- p \rightarrow \eta \pi^- p$
1406 ±20	[3] ALDE	88B	GAM4	0	100 $\pi^- p \rightarrow \eta \pi^0 n$

[1] Natural parity exchange.
[2] Unnatural parity exchange.
[3] Seen in the P_0-wave intensity of the $\eta\pi^0$ system, unnatural parity exchange.

$\hat{\rho}(1405)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
333 ±50 OUR AVERAGE					
$310 \pm 50\ ^{+\ 50}_{-\ 30}$	ABELE	98B	CBAR		0.0 $\overline{p}n \rightarrow \pi^- \pi^0 \eta$
$385 \pm 40\ ^{+\ 65}_{-105}$	[4] THOMPSON	97	MPS		18 $\pi^- p \rightarrow \eta \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
143.2±12.5	[5] AOYAGI	93	BKEI		$\pi^- p \rightarrow \eta \pi^- p$
180 ±20	[6] ALDE	88B	GAM4	0	100 $\pi^- p \rightarrow \eta \pi^0 n$

[4] Resolution is not unfolded, natural parity exchange.
[5] Unnatural parity exchange.
[6] Seen in the P_0-wave intensity of the $\eta\pi^0$ system, unnatural parity exchange.

$\hat{\rho}(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\eta\pi^-$	seen
Γ_3	$\eta'\pi$	possibly seen

$\hat{\rho}(1405)$ BRANCHING RATIOS

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen	PROKOSHKIN	95B	GAM4		100 $\pi^- p \rightarrow \eta \pi^0 n$
not seen	[7] BUGG	94	RVUE		$\overline{p}p \rightarrow \eta 2\pi^0$
not seen	[8] APEL	81	NICE	0	40 $\pi^- p \rightarrow \eta \pi^0 n$

[7] Using Crystal Barrel data.
[8] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\eta\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	BELADIDZE	93	VES	$37\pi^- N \rightarrow \eta \pi^- N$

$\Gamma(\eta'\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	BELADIDZE	93	VES	$37\pi^- N \rightarrow \eta \pi^- N$

$\Gamma(\eta'\pi)/\Gamma(\eta\pi^0)$ Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.80	95	BOUTEMEUR	90	GAM4	100 $\pi^- p \rightarrow 4\gamma n$

$\hat{\rho}(1405)$ REFERENCES

ABELE	98B	PL B423 175	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
THOMPSON	97	PRL 79 1630	+Adams+	(E852 Collab.)
PROKOSHKIN	95B	PAN 58 606 Translated from YAF 58 662.	+Sadovski	(SERP)
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
AOYAGI	93	PL B314 246	+Fukui, Hasegawa+	(BKEI Collab.)
BELADIDZE	93	PL 313 276	+Berdnikov, Bityukov+	(VES Collab.)
BOUTEMEUR	90	Hadron 89 Conf. p 119	+Poulet	(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	88B	PL B205 397	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP) IGJPC
APEL	81	NP B193 269	+Augenstein, Bertolucci, Donskov+	(SERP, CERN)

OTHER RELATED PAPERS

LACOCK	97	PL B401 308	P. Lacock+	(EDIN, LIVP)
SVEC	97C	PR D56 4355	M. Svec	(MCGI)
PROKOSHKIN	95C	PAN 58 853 Translated from YAF 58 921.	+Sadovski	(SERP)
KALASHNIK...	94	ZPHY C62 323	Kalashnikova	(ITEP)
IDDIR	88	PL B205 564	+Le Yaouanc, Ono+	(ORSAY, TOKY)
TUAN	88	PL B213 537	+Ferbel, Dalitz	(HAWA, ROCH, OXFTP)
ZIELINSKI	87	ZPHY C34 255		(ROCH)

$f_1(1420)$

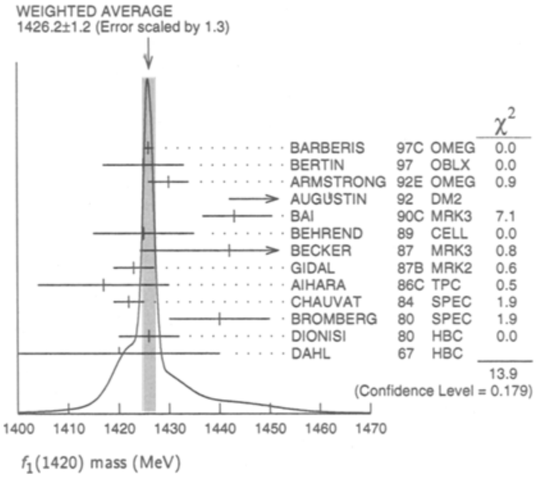
$I^G(J^{PC}) = 0^+(1^{++})$

See the minireview under $\eta(1440)$.

$f_1(1420)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1426.2± 1.2 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
1426 ± 1		BARBERIS	97C	OMEG	450 $pp \rightarrow pp K_S^0 K^\pm \pi^\mp$
1425 ± 8		BERTIN	97	OBLX	0.0 $\overline{p}p \rightarrow K^\pm (K^0) \pi^\mp \pi^+ \pi^-$
1430 ± 4		[1] ARMSTRONG	92E	OMEG	85,300 $\pi^+ p$, $pp \rightarrow \pi^+ p$, $pp(K\overline{K}\pi)$
1462 ±20		[2] AUGUSTIN	92	DM2	$J/\psi \rightarrow \gamma K\overline{K}\pi$
$1443\ ^{+\ 7}_{-\ 6}\ ^{+\ 3}_{-\ 2}$	1100	BAI	90C	MRK3	$J/\psi \rightarrow \gamma K_S^0 K^\pm \pi^\mp$
1425 ±10	17	BEHREND	89	CELL	$\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$
$1442 \pm 5\ ^{+10}_{-17}$	111	BECKER	87	MRK3	$e^+ e^-$, $\omega K\overline{K}\pi$
1423 ± 4		GIDAL	87B	MRK2	$e^+ e^- \rightarrow e^+ e^- K\overline{K}\pi$
1417 ±13	13	AIHARA	86C	TPC	$e^+ e^- \rightarrow e^+ e^- K\overline{K}\pi$
1422 ± 3		CHAUVAT	84	SPEC	ISR 31.5 pp
1440 ±10		[3] BROMBERG	80	SPEC	100 $\pi^- p \rightarrow K\overline{K}\pi X$
1426 ± 6	221	DIONISI	80	HBC	4 $\pi^- p \rightarrow K\overline{K}\pi n$
1420 ±20		DAHL	67	HBC	1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1429 ± 3	389	ARMSTRONG	89	OMEG	300 $pp \rightarrow K\overline{K}\pi pp$
1425 ± 2	1520	ARMSTRONG	84	OMEG	85 $\pi^+ p$, $pp \rightarrow (\pi^+, p)(K\overline{K}\pi)p$
~ 1420		BITYUKOV	84	SPEC	32 $K^- p \rightarrow K^+ K^- \pi^0 Y$

[1] This result supersedes ARMSTRONG 84, ARMSTRONG 89.
[2] From fit to the $K^*(892)K\ 1^{++}$ partial wave.
[3] Mass error increased to account for $a_0(980)$ mass cut uncertainties.



$f_1(1420)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
55.0± 3.0 OUR AVERAGE				
58 ± 4		BARBERIS 97C	OMEG	$450\ pp \to ppK^0_S K^\pm \pi^\mp$
45 ±10		BERTIN 97	OBLX	$0.0\ \overline{p}p \to K^\pm (K^0) \pi^\mp \pi^+ \pi^-$
58 ±10		[4] ARMSTRONG 92E	OMEG	$85{,}300\ \pi^+ p,\ pp \to \pi^+ p,\ pp(K\overline{K}\pi)$
129 ±41		[5] AUGUSTIN 92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$68\ {}^{+29}_{-18}\ {}^{+8}_{-9}$	1100	BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
42 ±22	17	BEHREND 89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
$40\ {}^{+17}_{-13}\ \pm 5$	111	BECKER 87	MRK3	$e^+ e^- \to \omega K\overline{K}\pi$
$35\ {}^{+47}_{-20}$	13	AIHARA 86C	TPC	$e^+ e^- \to e^+ e^- K\overline{K}\pi$
47 ±10		CHAUVAT 84	SPEC	ISR 31.5 pp
62 ±14		BROMBERG 80	SPEC	$100\ \pi^- p \to K\overline{K}\pi X$
40 ±15	221	DIONISI 80	HBC	$4\ \pi^- p \to K\overline{K}\pi n$
60 ±20		DAHL 67	HBC	$1.6\text{–}4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
58 ± 8	389	ARMSTRONG 89	OMEG	$300\ pp \to K\overline{K}\pi pp$
62 ± 5	1520	ARMSTRONG 84	OMEG	$85\ \pi^+ p,\ pp \to (\pi^+, p)(K\overline{K}\pi)p$
~ 50		BITYUKOV 84	SPEC	$32\ K^- p \to K^+ K^- \pi^0 Y$

[4] This result supersedes ARMSTRONG 84, ARMSTRONG 89.

[5] From fit to the $K^*(892)K\ 1^{++}$ partial wave.

$f_1(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	dominant
Γ_2	$K\overline{K}^*(892)+$ c.c.	dominant
Γ_3	$\eta\pi\pi$	possibly seen
Γ_4	$a_0(980)\pi$	
Γ_5	$\pi\pi\rho$	
Γ_6	4π	
Γ_7	$\gamma\gamma^*$	
Γ_8	$\rho^0\gamma$	

$f_1(1420)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.7±0.4 OUR AVERAGE				
3.0±0.9±0.7		[6,7] BEHREND 89	CELL	$e^+ e^- \to e^+ e^- K^0_S K\pi$
$2.3^{+1.0}_{-0.9}\pm 0.8$		HILL 89	JADE	$e^+ e^- \to e^+ e^- K^\pm K^0_S \pi^\mp$
1.3±0.5±0.3		AIHARA 88B	TPC	$e^+ e^- \to e^+ e^- K^\pm K^0_S \pi^\mp$
1.6±0.7±0.3		[6,8] GIDAL 87B	MRK2	$e^+ e^- \to e^+ e^- K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.0	95	JENNI 83	MRK2	$e^+ e^- \to e^+ e^- K\overline{K}\pi$

[6] Assume a ρ-pole form factor.

[7] A ϕ - pole form factor gives considerably smaller widths.

[8] Published value divided by 2.

$f_1(1420)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K}\pi)$ — Γ_2/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.76±0.06	BROMBERG 80	SPEC	$100\ \pi^- p \to K\overline{K}\pi X$
0.86±0.12	DIONISI 80	HBC	$4\ \pi^- p \to K\overline{K}\pi n$

$\Gamma(\pi\pi\rho)/\Gamma(K\overline{K}\pi)$ — Γ_5/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	95	CORDEN 78	OMEG	$12\text{–}15\ \pi^- p$
<2.0		DAHL 67	HBC	$1.6\text{–}4.2\ \pi^- p$

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ — Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.1	95	ARMSTRONG 91B	OMEG	$300\ pp \to pp\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.35±0.75		KOPKE 89	MRK3	$J/\psi \to \omega\eta\pi\pi(K\overline{K}\pi)$
<0.6	90	GIDAL 87	MRK2	$e^+ e^- \to e^+ e^- \eta\pi^+\pi^-$
<0.5	95	CORDEN 78	OMEG	$12\text{–}15\ \pi^- p$
1.5 ±0.8		DEFOIX 72	HBC	$0.7\ \overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ — Γ_4/Γ_3

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen in either mode	ANDO 86	SPEC	$8\ \pi^- p$
not seen in either mode	CORDEN 78	OMEG	$12\text{–}15\ \pi^- p$
0.4±0.2	DEFOIX 72	HBC	$0.7\ \overline{p}p \to 7\pi$

$\Gamma(4\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_6/Γ_2

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.90	95	DIONISI 80	HBC	$4\ \pi^- p$

$\Gamma(K\overline{K}\pi)/[\Gamma(K\overline{K}^*(892)+\text{c.c.})+\Gamma(a_0(980)\pi)]$ — $\Gamma_1/(\Gamma_2+\Gamma_4)$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.65±0.27	[9] DIONISI 80	HBC	$4\ \pi^- p$

[9] Calculated using $\Gamma(K\overline{K})/\Gamma(\eta\pi) = 0.24 \pm 0.07$ for $a_0(980)$ fractions.

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_4/Γ_2

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.04	68	ARMSTRONG 84	OMEG	$85\ \pi^+ p$

$\Gamma(4\pi)/\Gamma(K\overline{K}\pi)$ — Γ_6/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.62	95	ARMSTRONG 89G	OMEG	$85\ \pi p \to 4\pi X$

$\Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.08	95	[10] ARMSTRONG 92C	SPEC	$300\ pp \to pp\pi^+\pi^-\gamma$

[10] Using the data on the $\overline{K}K\pi$ mode from ARMSTRONG 89.

$f_1(1420)$ REFERENCES

BARBERIS	97C	PL B413 225	D. Barberis+	(WA102 Collab.)	
BERTIN	97	PL B400 226	+Bruschi, Capponi+	(OBELIX Collab.)	
ARMSTRONG	92C	ZPHY C54 371	+Barnes, Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)	
ARMSTRONG	92E	ZPHY 56 29	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)	JPC
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)	
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)	
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)	
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)	JPC
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)	
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)	
HILL	89	ZPHY C42 355	+Olsson+	(JADE Collab.)	JP
KOPKE	89	PRPL 174 67	+Wermes+	(CERN)	
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)	
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)	JP
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)	
GIDAL	87B	PRL 59 2016	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)	
AIHARA	86C	PRL 57 2500	+Alston-Garnjost+	(TPC-2γ Collab.)	JP
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+)	
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)	JP
BITYUKOV	84	SJNP 39 735 Translated from YAF 39 1165.	S. Bityukov+	(SERP)	
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, CLER, UCLA, SACL)	
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)	
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)	
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)	IJP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)	
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)	
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)	IJP
Also	65	PRL 14 1074	Miller, Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)	

OTHER RELATED PAPERS

IIZUKA	91	PTP 86 885	+Koibuchi	(NAGO)	
ISHIDA	89	PTP 82 119	+Oda, Sawazaki, Yamada	(NIHO)	
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.)	JPC
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)	
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)	

$\omega(1420)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(1420)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1419±31	315	[1] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1440±70		[2] CLEGG	94	RVUE	

[1] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

[2] Using data published by ANTONELLI 92.

$\omega(1420)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
174±59	315	[3] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
240±70		[4] CLEGG	94	RVUE	

[3] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

[4] Using data published by ANTONELLI 92.

$\omega(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	dominant
Γ_2	$\omega\pi\pi$	
Γ_3	e^+e^-	

$\omega(1420)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ **$\Gamma_1\Gamma_3/\Gamma$**

VALUE (eV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
81±31	315	[5] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \rightarrow \rho\pi$

[5] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

$\omega(1420)$ REFERENCES

CLEGG 94 ZPHY C62 455 +Donnachie (LANC, MCHS)
ANTONELLI 92 ZPHY C56 15 +Baldini+ (DM2 Collab.)

OTHER RELATED PAPERS

ACHASOV 97F PAN 60 2029 N.N. Achasov, Kozhevnikov (NOVM)
Translated from YAF 60 2212.
ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, CURIN)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)

$f_2(1430)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry lists nearby peaks observed in the D wave of the $K\overline{K}$ and $\pi^+\pi^-$ systems. Needs confirmation.

$f_2(1430)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 1430 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1421± 5	AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma\pi^+\pi^-$
1480±50	AKESSON	86	SPEC	$pp \rightarrow pp\pi^+\pi^-$
1436^{+26}_{-16}	DAUM	84	CNTR	17–18 $\pi^- p \rightarrow K^+K^-n$
1412± 3	DAUM	84	CNTR	63 $\pi^- p \rightarrow K^0_S K^0_S n$, K^+K^-n
1439^{+5}_{-6}	[1] BEUSCH	67	OSPK	5,7,12 $\pi^- p \rightarrow K^0_S K^0_S n$

[1] Not seen by WETZEL 76.

$f_2(1430)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30± 9	AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma\pi^+\pi^-$
150±50	AKESSON	86	SPEC	$pp \rightarrow pp\pi^+\pi^-$
81^{+56}_{-29}	DAUM	84	CNTR	17–18 $\pi^- p \rightarrow K^+K^-n$
14± 6	DAUM	84	CNTR	63 $\pi^- p \rightarrow K^0_S K^0_S n$, K^+K^-n
43^{+17}_{-18}	[2] BEUSCH	67	OSPK	5,7,12 $\pi^- p \rightarrow K^0_S K^0_S n$

[2] Not seen by WETZEL 76.

$f_2(1430)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\pi\pi$

$f_2(1430)$ REFERENCES

AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
DAUM 84 ZPHY C23 339 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
WETZEL 76 NP B115 208 +Freudenreich, Beusch+ (ETH, CERN, LOIC)
BEUSCH 67 PL 25B 357 +Fischer, Gobbi, Astbury+ (ETH, CERN)

$\eta(1440)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

THE $\eta(1440)$, $f_1(1420)$, AND $f_1(1510)$

Written March 1998 by M. Aguilar-Benitez (CIEMAT, Madrid) and C. Amsler (Zürich).

The first observation of $\eta(1440)$ was made in $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \rightarrow K\overline{K}\pi$ (BAILLON 67). This state was reported to decay through $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ has also been observed in radiative $J/\psi(1S)$ decay to $K\overline{K}\pi$ (SCHARRE 80, EDWARDS 82E, AUGUSTIN 90).

The $f_1(1420)$, decaying to $K^*\overline{K}$ was reported in π^-p reactions at 4 GeV/c (DIONISI 80). However, later analyses found that the 1400–1500 MeV region is far more complex. In π^-p experiments (CHUNG 85, REEVES 86, BIRMAN 88) reported 0^{-+} with a dominant $a_0(980)\pi$ contribution to $K\overline{K}\pi$. The π^-p data of RATH 89 at 21 GeV/c suggest the presence of two pseudoscalars decaying to $K\overline{K}\pi$, one around 1410 MeV decaying through $a_0(980)\pi$ and the other around 1470 MeV, decaying to $K^*\overline{K}$. A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay to $K\overline{K}\pi$ (BAI 90C) also claims the existence of two pseudoscalars in the 1400–1500 MeV range, the lower mass state decaying through $a_0(980)\pi$ and the higher mass state decaying via $K^*\overline{K}$. In addition, $f_1(1420)$ is observed to decay into $K^*\overline{K}$.

In $\pi^-p \rightarrow \eta\pi\pi n$ charge-exchange reactions at 8–9 GeV/c the $\eta\pi\pi$ mass spectrum is dominated by $\eta(1440)$ and $\eta(1295)$ (ANDO 86, FUKUI 91C) and at 100 GeV ALDE 97B report $\eta(1295)$ and $\eta(1440)$ decaying to $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ and no evidence for $f_1(1420)$.

An experiment in $\overline{p}p$ annihilation at rest into $K\overline{K}3\pi$ (BERTIN 95) reports two pseudoscalars with decay properties similar to BAI 90C, although the lower state shows, apart from $a_0(980)\pi$, a large contribution from the direct decay $\eta(1440) \to K\overline{K}\pi$. We note that the data from AUGUSTIN 92 also suggest two states but their intermediate states, $a_0(980)\pi$ and $K^*\overline{K}$, are reversed relative to BAI 90C.

In $J/\psi(1S)$ radiative decay $\eta(1440)$ decays to $K\overline{K}\pi$ through $a_0(980)\pi$ and hence a signal is also expected in the $\eta\pi\pi$ mass spectrum. This has indeed been observed by MARK III in $\eta\pi^+\pi^-$ (BOLTON 92B) which report a mass of 1400 MeV, in line with the existence of a low mass pseudoscalar in the $\eta(1440)$ structure, decaying to $a_0(980)\pi$. This state is also observed in $\overline{p}p$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$ where it decays to $\eta\pi\pi$ (AMSLER 95F). The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ rate, in accord with MARK III (BOLTON 92B) and DM2 (AUGUSTIN 90). However, ALDE 97B reports only a very small contribution of $a_0(980)\pi$.

One of these two pseudoscalars could be the first radial excitation of the η', with $\eta(1295)$ the first radial of the η. Ideal mixing suggested by the $\eta(1295)$ and $\pi(1300)$ mass degeneracy would then imply that the second isoscalar in the nonet is mainly $s\overline{s}$ and hence couples to $K^*\overline{K}$, in accord with observations for the upper $\eta(1440)$ state. This scheme then favors an exotic interpretation of the lower state, perhaps gluonium mixed with $q\overline{q}$ (CLOSE 97B) or a bound state of gluinos (FARRAR 96). The gluonium interpretation is, however, not favoured by lattice gauge theories, which predict the 0^{-+} state above 2 GeV (BALI 93).

Axial (1^{++}) mesons are not observed in $\overline{p}p$ annihilation at rest in liquid hydrogen which proceeds dominantly through S-wave annihilation. However, in gaseous hydrogen P-wave annihilation is enhanced and, indeed, BERTIN 97 report $f_1(1420)$ decaying to $K^*\overline{K}$ in gaseous hydrogen, while confirming their earlier evidence for two pseudoscalars (BERTIN 95).

In $\gamma\gamma$ fusion from e^+e^- annihilations, a signal around 1420 MeV is seen in single-tag events (GIDAL 87B, AIHARA 88B, BEHREND 89, HILL 89) where one of the two photons is off-shell. However, it is totally absent in the untagged events where both photons are real. This points to a spin 1 object which is not produced by two real (massless) photons (Yang-Landau theorem). The 2γ decays also implies $C = +1$. For the parity, AIHARA 88C and BEHREND 89 both find angular distributions with positive parity preferred, but negative parity cannot be excluded.

The $f_1(1420)$ is definitively observed in $K\overline{K}\pi$ in pp central production at 300 and 450 GeV, together with $f_1(1285)$. The latter decays via $a_0(980)\pi$ and the former only via $K^*\overline{K}$, while $\eta(1440)$ is absent (ARMSTRONG 89, BARBERIS 97C). The $K_SK_S\pi^0$ decay mode of $f_1(1420)$ establishes unambiguously that C=+1. On the other hand, there is no evidence for any state decaying to $\eta\pi\pi$ around 1400 MeV and hence the $\eta\pi\pi$ mode of $f_1(1420)$ is suppressed (ARMSTRONG 91B).

We now turn to the experimental evidence for $f_1(1510)$. Two states, $f_1(1420)$ and $f_1(1510)$, decaying to $K^*\overline{K}$, compete for the $s\overline{s}$ assignment in the 1^{++} nonet. The $f_1(1510)$ was seen in $K^-p \to \Lambda K\overline{K}\pi$ at 4 GeV/c (GAVILLET 82) and at 11 GeV/c (ASTON 88C). Evidence is also reported in π^-p at 8 GeV/c, based on the phase motion of the 1^{++} $K^*\overline{K}$ wave (BIRMAN 88).

The absence of $f_1(1420)$ in K^-p (ASTON 88C) argues against $f_1(1420)$ being the $s\overline{s}$ member of the 1^{++} nonet. However, $f_1(1420)$ has been reported in K^-p but not in π^-p (BITYUKOV 84) while two experiments do not observe $f_1(1510)$ in K^-p (BITYUKOV 84, KING 91). It is also not seen in radiative $J/\psi(1S)$ decay (BAI 90C, AUGUSTIN 92), central collisions (BARBERIS 97C), nor in $\gamma\gamma$ collisions (AIHARA 88C), although and surprisingly for an $s\overline{s}$ state, a signal is reported in 4π decays (BAUER 93B). These facts led to the conclusion that $f_1(1510)$ is not well established and that its assignment as $s\overline{s}$ member of the 1^{++} nonet is premature (CLOSE 97D). The Particle Data Group agrees and has removed this state from the Summary Table. Assigning instead $f_1(1420)$ to the 1^{++} nonet one finds a nonet mixing angle of $\sim 50°$ (CLOSE 97D). This is derived from the mass formula and from $f_1(1285)$ radiative decays to $\phi\gamma$ (BITYUKOV 88) and $\rho\gamma$ (AMELIN 95).

Arguments favoring $f_1(1420)$ being a hybrid $q\overline{q}g$ meson or a four-quark state are put forward by ISHIDA 89 and by CALDWELL 90, respectively, while LONGACRE 90 argues that this particle is a molecular state formed by the π orbiting in a P-wave around an S-wave $K\overline{K}$ state.

Summarizing, there is strong evidence for $f_1(1420)$, mostly produced in central collisions and decaying to $K^*\overline{K}$, and for $\eta(1440)$ mostly produced in radiative $J/\psi(1S)$ decay and $\overline{p}p$ annihilation at rest, decaying to $K^*\overline{K}$ and $a_0(980)\pi$. Confusion remains as to which states are observed in π^-p interactions. The $f_1(1510)$ is not well established. Furthermore, there are experimental indications for the presence of two pseudoscalars in the $\eta(1440)$ structure. Accordingly, the Particle Data Group has split the $K\overline{K}\pi$ entry for $\eta(1440)$ into $a_0(980)\pi$ and $K^*\overline{K}$.

$\eta(1440)$ MASS

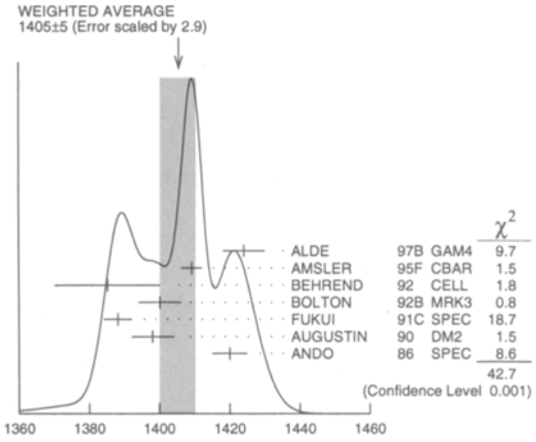
VALUE (MeV)	*DOCUMENT ID*
1400 - 1470 OUR ESTIMATE	Contains possibly two overlapping pseudoscalars.

$\eta\pi\pi$ MODE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1405± 5 OUR AVERAGE		Error includes scale factor of 2.9. See the ideogram below.			
1424± 6	2200	ALDE	97B	GAM4	100 $\pi^-p \to \eta\pi^0\pi^0n$
1409± 3		AMSLER	95F	CBAR	0 $\overline{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$
1385±15		[1] BEHREND	92	CELL	$J/\psi \to \gamma\eta\pi^+\pi^-$
1400± 6		[1] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
1388± 4		FUKUI	91C	SPEC	8.95 $\pi^-p \to \eta\pi^+\pi^-n$
1398± 6	261	[2] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
1420± 5		ANDO	86	SPEC	8 $\pi^-p \to \eta\pi^+\pi^-n$

[1] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.

[2] Best fit with a single Breit Wigner.



$\eta(1440)$ mass, $\eta\pi\pi$ mode (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1401 ± 18	[3,4] AUGUSTIN	90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
1440 ± 20	[4] COFFMAN	90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[3] Best fit with a single Breit Wigner.

[4] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1420 ± 20		BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1489 ± 12	3270	[5] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[5] Estimated by us from various fits.

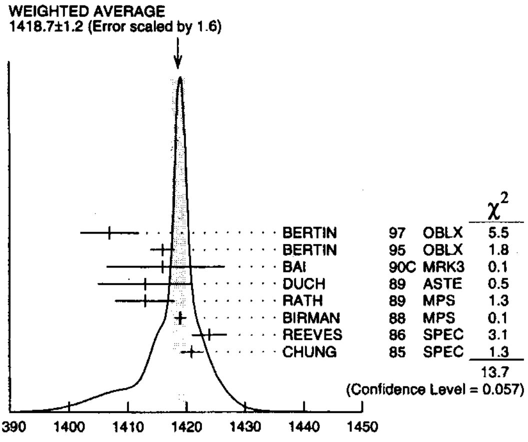
$K\overline{K}\pi$ MODE ($a_0(980)\,\pi$ dominant)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1418.7±1.2 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
1407 ± 5		[6] BERTIN	97	OBLX	$0\,\overline{p}p \to K^\pm(K^0)\pi^\mp\pi^+\pi^-$
1416 ± 2		[6] BERTIN	95	OBLX	$0\,\overline{p}p \to K\overline{K}\pi\pi\pi$
$1416 \pm 8\,^{+7}_{-5}$	700	[7] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1413 ± 8	500	DUCH	89	ASTE	$\overline{p}p \to \pi^+\pi^- K^\pm\pi^\mp K^0$
1413 ± 5		[7] RATH	89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
1419 ± 1	8800	BIRMAN	88	MPS	$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
1424 ± 3	620	REEVES	86	SPEC	$6.6\ p\overline{p} \to K\overline{K}\pi X$
1421 ± 2		CHUNG	85	SPEC	$8\ \pi^- p \to K\overline{K}\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1459 ± 5		[8] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$

[6] Decaying into $(K\overline{K})_S\pi$, $(K\pi)_S\overline{K}$, and $a_0(980)\pi$.

[7] From fit to the $a_0(980)\pi\ 0^{-+}$ partial wave. Cannot rule out a $a_0(980)\pi\ 1^{++}$ partial wave.

[8] Excluded from averaging because averaging would be meaningless.



$\eta(1440)$ mass, $K\overline{K}\pi$ mode ($a_0(980)\ \pi$ dominant) (MeV)

$K\overline{K}\pi$ MODE ($K^*(892)\ K$ dominant)

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1473± 4 OUR AVERAGE	Error includes scale factor of 1.1.				
1464 ± 10		BERTIN	97	OBLX	$0\,\overline{p}p \to K^\pm(K^0)\pi^\mp\pi^+\pi^-$
1460 ± 10		BERTIN	95	OBLX	$0\,\overline{p}p \to K\overline{K}\pi\pi\pi$
$1490\,^{+14}_{-8}\,^{+3}_{-16}$	1100	BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1475 ± 4		RATH	89	MPS	$21.4\ \pi^- p \to n K^0_S K^0_S \pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1421 ± 14		[9] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$

[9] Excluded from averaging because averaging would be meaningless.

$K\overline{K}\pi$ MODE (unresolved)

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1445 ± 8	693	AUGUSTIN	90	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1433 ± 8	296	AUGUSTIN	90	DM2	$J/\psi \to \gamma K^+ K^- \pi^0$
1453 ± 7	170	RATH	89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
$1440\,^{+20}_{-15}$	174	EDWARDS	82E	CBAL	$J/\psi \to \gamma K^+ K^- \pi^0$
$1440\,^{+10}_{-15}$		SCHARRE	80	MRK2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1425 ± 7	800	[10] BAILLON	67	HBC	$0\,\overline{p}p \to K\overline{K}\pi\pi\pi$

[10] From best fit of 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.

$\eta(1440)$ WIDTH

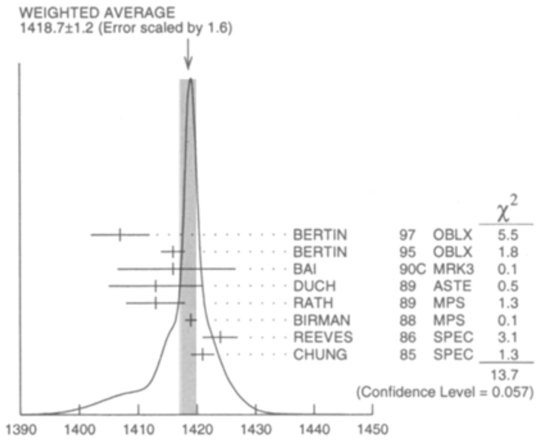
VALUE (MeV)	DOCUMENT ID
50 - 80 OUR ESTIMATE	Contains possibly two overlapping pseudoscalars.

$\eta\pi\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
56± 7 OUR AVERAGE	Error includes scale factor of 2.3. See the ideogram below.				
85 ± 18	2200	ALDE	97B	GAM4	$100\ \pi^- p \to \eta\pi^0\pi^0 n$
86 ± 10		AMSLER	95F	CBAR	$0\,\overline{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$
47 ± 13		[11] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
59 ± 4		FUKUI	91C	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
53 ± 11		[12] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
31 ± 7		ANDO	86	SPEC	$8\ \pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 50		[12] BEHREND	92	CELL	$J/\psi \to \gamma\eta\pi^+\pi^-$

[11] From fit to the $a_0(980)\pi\ 0^{-+}$ partial wave.

[12] From $\eta\pi^+\pi^-$ mass distribution - mainly $a_0(980)\pi$ - no spin–parity determination available.



$\eta(1440)$ mass, $K\overline{K}\pi$ mode ($a_0(980)\ \pi$ dominant) (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
174 ± 44	AUGUSTIN	90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
60 ± 30	[13] COFFMAN	90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[13] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
160 ± 30		BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
144 ± 13	3270	[14] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

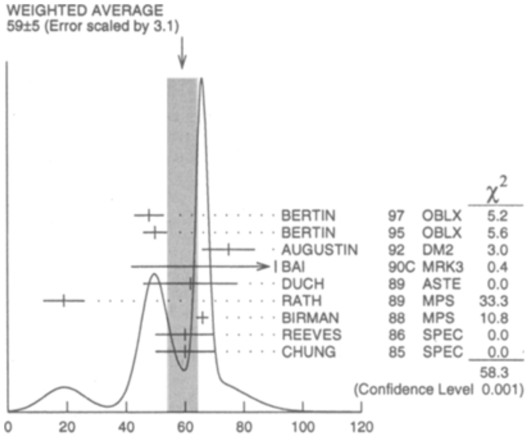
[14] Estimated by us from various fits.

$K\overline{K}\pi$ MODE ($a_0(980)$ π dominant)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
59± 5 OUR AVERAGE	Error includes scale factor of 3.1. See the ideogram below.			
48 ± 5		[15] BERTIN 97	OBLX	$0.0\ \overline{p}p \to K^{\pm}(K^0)\pi^{\mp}\pi^+\pi^-$
50 ± 4		[15] BERTIN 95	OBLX	$0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
75 ± 9		AUGUSTIN 92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$91^{+67}_{-31}{}^{+15}_{-38}$		[16] BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$
62 ± 16	500	DUCH 89	ASTE	$\overline{p}p \to K\overline{K}\pi\pi\pi$
19 ± 7		[16] RATH 89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S\pi^0$
66 ± 2	8800	BIRMAN 88	MPS	$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
60 ± 10	620	REEVES 86	SPEC	$6.6\ p\overline{p} \to KK\pi X$
60 ± 10		CHUNG 85	SPEC	$8\ \pi^- p \to K\overline{K}\pi n$

[15] Decaying into $(K\overline{K})_S\pi$, $(K\pi)_S\overline{K}$, and $a_0(980)\pi$.

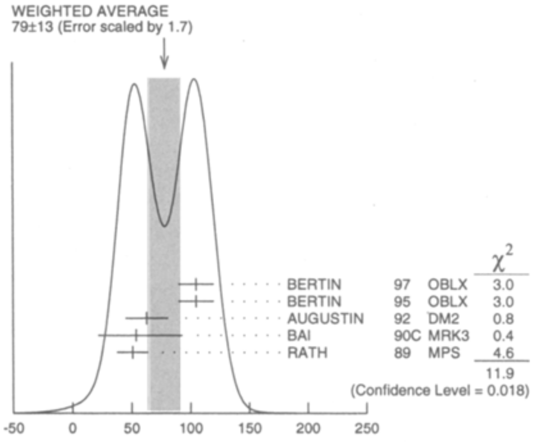
[16] From fit to the $a_0(980)\pi$ 0^{-+} partial wave , but $a_0(980)\pi$ 1^{++} cannot be excluded.



$\eta(1440)$ width $K\overline{K}\pi$ mode ($a_0(980)$ π dominant)

$K\overline{K}\pi$ MODE ($K^*(892)$ K dominant)

VALUE	DOCUMENT ID	TECN	COMMENT
79±13 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.		
105 ± 15	BERTIN 97	OBLX	$0.0\ \overline{p}p \to K^{\pm}(K^0)\pi^{\mp}\pi^+\pi^-$
105 ± 15	BERTIN 95	OBLX	$0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
63 ± 18	AUGUSTIN 92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$54^{+37}_{-21}{}^{+13}_{-24}$	BAI 90C	MRK3	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$
51 ± 13	RATH 89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S\pi^0$



$\eta(1440)$ width $K\overline{K}\pi$ mode ($K^*(892)$ K dominant)

$K\overline{K}\pi$ MODE (unresolved)

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93 ± 14	296	AUGUSTIN 90	DM2	$J/\psi \to \gamma K^+K^-\pi^0$
105 ± 10	693	AUGUSTIN 90	DM2	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$
100 ± 11	170	RATH 89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S\pi^0 n$
55^{+20}_{-30}	174	EDWARDS 82E	CBAL	$J/\psi \to \gamma K^+K^-\pi^0$
50^{+30}_{-20}		SCHARRE 80	MRK2	$J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$
80 ± 10	800	[17] BAILLON 67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$

[17] From best fit to 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.

$\eta(1440)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	seen
Γ_2	$K\overline{K}^*(892)+$ c.c.	seen
Γ_3	$\eta\pi\pi$	seen
Γ_4	$a_0(980)\pi$	seen
Γ_5	$\eta(\pi\pi)_{S\text{-wave}}$	seen
Γ_6	4π	seen
Γ_7	$\gamma\gamma$	
Γ_8	$\rho^0\gamma$	

$\eta(1440)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<1.2	95	BEHREND 89	CELL	$\gamma\gamma \to K^0_S K^{\pm}\pi^{\mp}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.6	95	AIHARA 86D	TPC	$e^+e^- \to e^+e^- K^0_S K^{\pm}\pi^{\mp}$
<2.2	95	ALTHOFF 85B	TASS	$e^+e^- \to e^+e^- K\overline{K}\pi$
<8.0	95	JENNI 83	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_3\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.3	ANTREASYAN 87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\Gamma(\rho^0\gamma) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_8\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.5	95	ALTHOFF 84E	TASS	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$

$\eta(1440)$ BRANCHING RATIOS

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.5	90	EDWARDS 83B	CBAL	$J/\psi \to \eta\pi\pi\gamma$
<1.1	90	SCHARRE 80	MRK2	$J/\psi \to \eta\pi\pi\gamma$
<1.5	95	FOSTER 68B	HBC	$0.0\ \overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}\pi)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.15		[18] BERTIN 95	OBLX	$0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
~ 0.8	500	[18] DUCH 89	ASTE	$\overline{p}p \to \pi^+\pi^- K^{\pm}\pi^{\mp}K^0$
~ 0.75		[18] REEVES 86	SPEC	$6.6\ p\overline{p} \to KK\pi X$

[18] Assuming that the $a_0(980)$ decays only into $K\overline{K}$.

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ — Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.19 ± 0.04	2200	[19] ALDE 97B	GAM4	$100\ \pi^- p \to \eta\pi^0\pi^0 n$
$0.56\pm 0.04\pm 0.03$		[19] AMSLER 95F	CBAR	$0\ \overline{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$

[19] Assuming that the $a_0(980)$ decays only into $\eta\pi$.

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K}\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.50±0.10	BAILLON 67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/[\Gamma(K\overline{K}^*(892)+\text{c.c.})+\Gamma(a_0(980)\pi)]$ — $\Gamma_2/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.25	90	EDWARDS 82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$

$\Gamma(\rho^0\gamma)/\Gamma(K\overline{K}\pi)$ — Γ_8/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0152±0.0038	[20] COFFMAN	90	MRK3	$J/\psi \rightarrow \gamma\gamma\pi^+\pi^-$

[20] Using B($J/\psi \rightarrow \gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi$)=$4.2 \times 10^{-3}$ and B($J/\psi \rightarrow \gamma\eta(1440) \rightarrow \gamma\gamma\rho^0$)=$6.4 \times 10^{-5}$ and assuming that the $\gamma\rho^0$ signal does not come from the $f_1(1420)$.

$\Gamma(\eta(\pi\pi)_{S\text{-wave}})/\Gamma(\eta\pi\pi)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.81±0.04	2200	ALDE	97B	GAM4	100 $\pi^- p \rightarrow \eta\pi^0\pi^0 n$

$\eta(1440)$ REFERENCES

ALDE	97B	PAN 60 386 Translated from YAF 60 458.	D. Alde, Binon, Bricman+	(GAMS Collab.)
BERTIN	97	PL B400 226	+Bruschi, Capponi+	(OBELIX Collab.)
AMSLER	95F	PL B358 389	+Armstrong, Urner+	(Crystal Barrel Collab.)
BERTIN	95	PL B361 187	+Bruschi+	(OBELIX Collab.)
BUGG	95	PL B353 378	+Scott, Zoll+	(LOQM, PNPI, WASH)
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)
BEHREND	92	ZPHY C56 381		(CELLO Collab.)
BOLTON	92B	PRL 69 1328	+Brown, Bunnell+	(Mark III Collab.)
FUKUI	91C	PL B267 293	+	(SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
DUCH	89	ZPHY 45 223	+Heel, Bailey+	(ASTERIX Collab.) JP
RATH	89	PR D40 693	+Cason+	(NDAM, BRAN, BNL, CUNY, DUKE)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, MASD) JP
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
AIHARA	86D	PRL 57 51	+Alston-Garnjost+	(TPC-2γ Collab.)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+) IJP
REEVES	86	PR 34 1960	+Chung, Crittenden+	(FLOR, BNL, IND, MASD) JP
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, MASD) JP
ALTHOFF	84E	PL 147B 487	+Braunschweig, Kirschfink, Luebelsmeyer+	(TASSO Collab.)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	PRL 50 219	Edwards, Partridge+	(CIT, HARV, PRIN, STAN+)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
FOSTER	68B	NP B8 174	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)
BAILLON	67	NC 50A 393	+Edwards, D'Andlau, Astier+	(CERN, CDEF, IRAD)

OTHER RELATED PAPERS

CLOSE	97B	PR D55 5749	F. Close+	(RAL, RUTG, BEIJT)
BERTIN	96	PL B385 493	+Bruschi+	(Obelix Collab.)
FARRAR	96	PRL 76 4111	G.R. Farrar	(RUTG)
AMELIN	95	ZPHY C66 71	+Berdnikov+	(VES Collab.)
GENOVESE	94	ZPHY C61 425	+Lichtenberg, Pedrazzi	(TORI, IND)
BALI	93	PL B309 378	+Schilling, Hulsebo, Irving, Michael+	(LIVP)
LONGACRE	90	PR D42 874		(BNL)
AHMAD	89	NP B (PROC.)8 50	+Amsler, Auld+	(ASTERIX Collab.)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
ARMSTRONG	87	ZPHY C34 23	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(PARIS, LIVP)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN)

$a_0(1450)$

$I^G(J^{PC}) = 1^-(0^{++})$

See minireview on scalar mesons under $f_0(1370)$.

$a_0(1450)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1474±19 OUR AVERAGE				
1480±30	ABELE	98	CBAR	0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
1470±25	[1] AMSLER	95D	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1450±40	AMSLER	94D	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\pi^0\eta$
1435±40	BUGG	94	RVUE	$\overline{p}p \rightarrow \eta 2\pi^0$

[1] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

$a_0(1450)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
265±13 OUR AVERAGE				
265±15	ABELE	98	CBAR	0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
265±30	[2] AMSLER	95D	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
270±40	AMSLER	94D	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\pi^0\eta$
270±40	BUGG	94	RVUE	$\overline{p}p \rightarrow \eta 2\pi^0$

[2] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

$a_0(1450)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\eta$	seen
Γ_2	$\pi\eta'(958)$	seen
Γ_3	$K\overline{K}$	seen

$\Gamma(\pi\eta'(958))/\Gamma(\pi\eta)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.35±0.16	[3] ABELE	98	CBAR	0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.43±0.19	ABELE	97C	CBAR	0.0 $\overline{p}p \rightarrow \pi^0\pi^0\eta'$

[3] Using $\pi^0\eta$ from AMSLER 94D.

$\Gamma(K\overline{K})/\Gamma(\pi\eta)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.88±0.23	[3] ABELE	98	CBAR	0.0 $\overline{p}p \rightarrow K^0_L K^\pm\pi^\mp$

$a_0(1450)$ REFERENCES

ABELE	98	PR D57 3860	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
ABELE	97C	PL B404 179	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.) IGJPC
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)

$\rho(1450)$

$I^G(J^{PC}) = 1^+(1^{--})$

See the mini-review under the $\rho(1700)$.

$\rho(1450)$ MASS

VALUE (MeV)	DOCUMENT ID
1465±25 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1452± 8 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1470±20	ANTONELLI	88	DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$
1446±10	FUKUI	88	SPEC	8.95 $\pi^- p \rightarrow \eta\pi^+\pi^- n$

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1463±25	[1] CLEGG	94	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1250	[2] ASTON	80C	OMEG	20–70 $\gamma p \rightarrow \omega\pi^0 p$
1290±40	[2] BARBER	80C	SPEC	3–5 $\gamma p \rightarrow \omega\pi^0 p$

[1] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.

[2] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1348±33	BERTIN	98	OBLX	50–405 $\overline{n}p \rightarrow \pi^+\pi^+\pi^-$
1411±14	[3] ABELE	97	CBAR	$\overline{p}n \rightarrow \pi^-\pi^0\pi^0$
1370^{+90}_{-70}	ACHASOV	97	RVUE	$e^+e^- \rightarrow \pi^+\pi^-$
1380±24	[4] BARATE	97M	ALEP	$\tau^- \rightarrow \pi^-\pi^0\nu_\tau$
1359±40	[5] BERTIN	97C	OBLX	0.0 $\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
1282±37	BERTIN	97D	OBLX	0.05 $\overline{p}p \rightarrow 2\pi^+2\pi^-$
1424±25	BISELLO	89	DM2	$e^+e^- \rightarrow \pi^+\pi^-$

[3] T-matrix pole.

[4] Fixing $\rho(1450)$ width to 310 MeV and $\rho(1700)$ mass and width to 1700 MeV and 235 MeV respectively.

[5] $\rho(1700)$ mass and width fixed at 1700 MeV and 235 MeV, respectively.

$\pi^+\pi^-\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1350±50	ACHASOV	97	RVUE	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
1449± 4	[6] ARMSTRONG	89E	OMEG	300 $pp \rightarrow pp2(\pi^+\pi^-)$

[6] Not clear whether this observation has I=1 or 0.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1480±40	[7,8] BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[7] DONNACHIE 91 suggests this is a different particle.
[8] Not seen by ABELE 97H.

MIXED MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1265.5±75.3	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$

$\rho(1450)$ WIDTH

VALUE (MeV)	DOCUMENT ID
310±60 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
230±30	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
60±15	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
311± 62	[9] CLEGG	94	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300	[10] ASTON	80C	OMEG	20–70 $\gamma p \to \omega\pi^0 p$
320±100	[10] BARBER	80C	SPEC	3–5 $\gamma p \to \omega\pi^0 p$

[9] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.
[10] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
275±10	BERTIN	98	OBLX	50–405 $\overline{n}p \to \pi^+\pi^+\pi^-$
343±20	[11] ABELE	97	CBAR	$\overline{p}n \to \pi^-\pi^0\pi^0$
310±40	[12] BERTIN	97C	OBLX	0.0 $\overline{p}p \to \pi^+\pi^-\pi^0$
236±36	BERTIN	97D	OBLX	0.05 $\overline{p}p \to 2\pi^+2\pi^-$
269±31	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$

[11] T-matrix pole.
[12] $\rho(1700)$ mass and width fixed at 1700 MeV and 235 MeV, respectively.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
130±60	[13,14] BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[13] DONNACHIE 91 suggests this is a different particle.
[14] Not seen by ABELE 97H.

MIXED MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
391±70	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$

$\rho(1450)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	seen	
Γ_2	4π	seen	
Γ_3	$\omega\pi$	<2.0 %	95%
Γ_4	e^+e^-	seen	
Γ_5	$\eta\rho$	<4 %	
Γ_6	$\phi\pi$	<1 %	
Γ_7	$K\overline{K}$	$<1.6 \times 10^{-3}$	95%

$\rho(1450)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.12	[15] DIEKMAN	88	RVUE	$e^+e^- \to \pi^+\pi^-$

[15] Using total width = 235 MeV.

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_4/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
91±19	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(\phi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_6\Gamma_4/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<70	90	[16] AULCHENKO	87B	ND	$e^+e^- \to K^0_S K^0_L \pi^0$

[16] Using mass 1480 ± 40 MeV and total width 130 ± 60 MeV of BITYUKOV 87.

$\rho(1450)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN
<0.04	DONNACHIE	87B	RVUE

$\Gamma(\phi\pi)/\Gamma(\omega\pi)$ — Γ_6/Γ_3

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.5	95	BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

$\Gamma(\omega\pi)/\Gamma(4\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN
<0.14	CLEGG	88	RVUE

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ — Γ_5/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
~ 0.24	[17] DONNACHIE	91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>2	FUKUI	91	SPEC	8.95 $\pi^- p \to \omega\pi^0 n$

$\Gamma(\omega\pi)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN
~ 0.21	CLEGG	94	RVUE

$\Gamma(\pi\pi)/\Gamma(\omega\pi)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN
~ 0.32	CLEGG	94	RVUE

$\Gamma(\phi\pi)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.01	[17] DONNACHIE	91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ABELE	97H	CBAR	$\overline{p}p \to K^0_L K^0_S \pi^0\pi^0$

$\Gamma(K\overline{K})/\Gamma(\omega\pi)$ — Γ_7/Γ_3

VALUE	DOCUMENT ID		TECN
<0.08	[17] DONNACHIE	91	RVUE

[17] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.

$\rho(1450)$ REFERENCES

BERTIN	98	PR D57 55	A. Bertin, Bruschi, Capponi+	(OBELIX Collab.)
ABELE	97	PL B391 191	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
ABELE	97H	PL B415 280	A. Abele+	(Crystal Barrel Collab.)
ACHASOV	97	PR D55 2663	+Kozhevnikov+	(NOVM)
BARATE	97M	ZPHY C76 15	R. Barate+	(ALEPH Collab.)
BERTIN	97C	PL B408 476	A. Bertin, Bruschi+	(OBELIX Collab.)
BERTIN	97D	PL B414 220	A. Bertin+	(OBELIX Collab.)
CLEGG	94	ZPHY C62 455	+Donnachie	(LANC, MCHS)
BISELLO	91B	NP B21 111 (suppl)		(DM2 Collab.)
DONNACHIE	91	ZPHY C51 689	+Clegg	(MCHS, LANC)
FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, CURIN+)
BISELLO	89	PL B220 321	+Busetto+	(DM2 Collab.)
DUBNICKA	89	JPG 15 1349	+Martinovic+	(JINR, SLOV)
ANTONELLI	88	PL B212 133	+Baldini+	(DM2 Collab.)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
DIEKMAN	88	PRPL 159 101		(BONN)
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
ALBRECHT	87L	PL B185 223	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
AULCHENKO	87B	JETPL 45 145 Translated from ZETFP 45 118.	+Dolinsky, Druzhinin, Dubrovin+	(NOVO)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
DONNACHIE	87B	ZPHY C34 257	+Clegg	(MCHS, LANC)
DOLINSKY	86	PL B174 453	+Druzhinin, Dubrovin, Eidelman+	(NOVO)
ASTON	80C	PL 92B 211		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER	80C	ZPHY C4 169	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)

OTHER RELATED PAPERS

ABELE	97H	PL B415 280	A. Abele+	(Crystal Barrel Collab.)
BARNES	97	PR D55 4157	T. Barnes+	(ORNL, RAL, MCHS)
CLOSE	97C	PR D56 1584	F.E. Close+	(RAL, MCHS)
URHEIM	97	NPBPS 55C 359	J. Urheim	(CLEO Collab.)
ACHASOV	96B	PAN 59 1262 Translated from YAF 59 1319.	+Shestakov	(NOVM)
MURADOV	94	PAN 57 864		(BAKU)
LANDSBERG	92	SJNP 55 1051 Translated from YAF 55 1896.		(SERP)
BRAU	88	PR D37 2379	+Franek+	(SLAC Hybrid Facility Photon Collab.)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
KURDADZE	86	JETPL 43 643 Translated from ZETFP 43 497.	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)

BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
BISELLO 85 LAL 85-15 +Augustin, Ajaltouni+ (PADO, LALO, CLER, FRAS)
ABE 84B PRL 53 751 +Bacon, Ballam+ (SLAC Hybrid Facility Photon Collab.)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER 82 PL 109B 129 +Bisello, Bizot, Buon, Delcourt (LALO)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSAY)
BINGHAM 72B PL 41B 635 +Rabin, Rosenfeld, Smadja+ (LBL, UCB, SLAC)
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN)
LAYSSAC 71 NC 6A 134 +Renard (MONP)

$f_0(1500)$

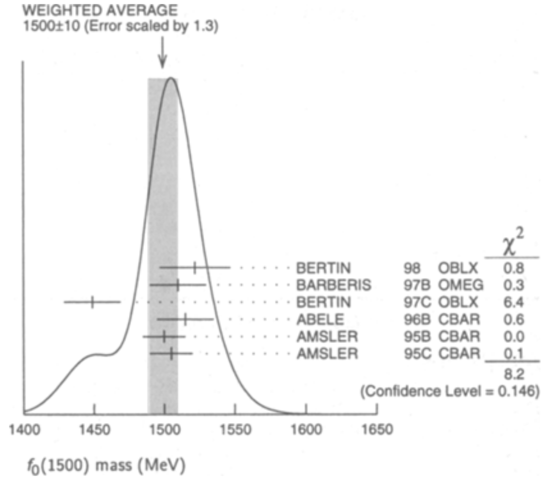
$I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-reviews on scalar mesons under $f_0(1370)$ and on non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_0(1500)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1500±10 OUR AVERAGE		Error includes scale factor of 1.3.		See the ideogram below.
1522±25		BERTIN 98	OBLX	50–405 $\overline{n}p \to \pi^+\pi^+\pi^-$
1510±20		[1] BARBERIS 97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
1449±20		[1] BERTIN 97C	OBLX	0.0 $\overline{p}p \to \pi^+\pi^-\pi^0$
1515±20		ABELE 96B	CBAR	0.0 $\overline{p}p \to \pi^0 K^0_L K^0_L$
1500±15		[2] AMSLER 95B	CBAR	0.0 $\overline{p}p \to 3\pi^0$
1505±15		[3] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1475		FRABETTI 97D	E687	$D^\pm_s \to \pi^\mp\pi^\pm\pi^\pm$
~ 1430		[4] KAMINSKI 97B	RVUE	$\pi^- p_{\text{polar}} \to \pi^+\pi^- n$
~ 1505		ABELE 96	CBAR	0.0 $\overline{p}p \to 5\pi^0$
1500± 8		[1] ABELE 96C	RVUE	Compilation
1460±20	120	[5] AMELIN 96B	VES	37 $\pi^- A \to \eta\eta\pi^- A$
1500± 8		BUGG 96	RVUE	
1500±10		[6] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
1445± 5		[7] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
1497±30		[5] ANTINORI 95	OMEG	300,450 $pp \to pp\pi^+\pi^-$
~ 1505		BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1446± 5		[5] ABATZIS 94	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
1545±25		[5] AMSLER 94E	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta'$
1520±25		[1,8] ANISOVICH 94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$
1505±20		[1,9] BUGG 94	RVUE	$\overline{p}p \to 3\pi^0$, $\eta\eta\pi^0$, $\eta\pi^0\pi^0$
1560±25		[5] AMSLER 92	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta$
1550±45±30		[5] BELADIDZE 92C	VES	36 $\pi^-\text{Be} \to \pi^-\eta'\eta\text{Be}$
1449± 4		[5] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$
1610±20		[5] ALDE 88	GAM4	300 $\pi^- N \to \pi^- N2\eta$
~ 1525		ASTON 88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
1570±20	600	[5] ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
1575±45		[10] ALDE 86D	GAM4	100 $\pi^- p \to 2\eta n$
1568±33		[5] BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$
1592±25		[5] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$
1525± 5		[5] GRAY 83	DBC	0.0 $\overline{p}N \to 3\pi$

[1] T-matrix pole.
[2] T-matrix pole, supersedes ANISOVICH 94.
[3] T-matrix pole, supersedes ANISOVICH 94 and AMSLER 92.
[4] Reanalysis of SRINIVASAN 75, ROSSELET 77, BECKER 79, and COHEN 80 using a three coupled channel analysis ($\pi\pi$, $K\overline{K}$, and $\sigma\sigma$).
[5] Breit-Wigner mass.
[6] T-matrix pole. Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[7] Supersedes ABATZIS 94, ARMSTRONG 89E. Breit-Wigner mass.
[8] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$.
[9] Reanalysis of ANISOVICH 94 data.
[10] From central value and spread of two solutions. Breit-Wigner mass.



$f_0(1500)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
112±10 OUR AVERAGE				
108±33		BERTIN 98	OBLX	50–405 $\overline{n}p \to \pi^+\pi^+\pi^-$
120±35		[11] BARBERIS 97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
114±30		[11] BERTIN 97C	OBLX	0.0 $\overline{p}p \to \pi^+\pi^-\pi^0$
105±15		ABELE 96B	CBAR	0.0 $\overline{p}p \to \pi^0 K^0_L K^0_L$
120±25		[12] AMSLER 95B	CBAR	0.0 $\overline{p}p \to 3\pi^0$
120±30		[13] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 100		FRABETTI 97D	E687	$D^\pm_s \to \pi^\mp\pi^\pm\pi^\pm$
~ 135		[14] KAMINSKI 97B	RVUE	$\pi^- p_{\text{polar}} \to \pi^+\pi^- n$
~ 169		ABELE 96	CBAR	0.0 $\overline{p}p \to 5\pi^0$
100±30	120	[15] AMELIN 96B	VES	37 $\pi^- A \to \eta\eta\pi^- A$
132±15		BUGG 96	RVUE	
154±30		[16] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
65±10		[17] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
199±30		[15] ANTINORI 95	OMEG	300,450 $pp \to pp\pi^+\pi^-$
56±12		[15] ABATZIS 94	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
100±40		[15] AMSLER 94E	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta'$
148^{+20}_{-25}		[11,18] ANISOVICH 94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$
150±20		[11,19] BUGG 94	RVUE	$\overline{p}p \to 3\pi^0$, $\eta\eta\pi^0$, $\eta\pi^0\pi^0$
245±50		[15] AMSLER 92	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta$
153±67±50		[15] BELADIDZE 92C	VES	36 $\pi^-\text{Be} \to \pi^-\eta'\eta\text{Be}$
78±18		[15] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$
170±40		[15] ALDE 88	GAM4	300 $\pi^- N \to \pi^- N2\eta$
150±20	600	[15] ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
265±65		[20] ALDE 86D	GAM4	100 $\pi^- p \to 2\eta n$
260±60		[15] BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$
210±40		[15] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$
101±13		[15] GRAY 83	DBC	0.0 $\overline{p}N \to 3\pi$

[11] T-matrix pole.
[12] T-matrix pole, supersedes ANISOVICH 94.
[13] T-matrix pole, supersedes ANISOVICH 94 and AMSLER 92.
[14] Reanalysis of SRINIVASAN 75, ROSSELET 77, BECKER 79, and COHEN 80 using a three coupled channel analysis ($\pi\pi$, $K\overline{K}$, and $\sigma\sigma$).
[15] Breit-Wigner mass.
[16] T-matrix pole. Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[17] Supersedes ABATZIS 94, ARMSTRONG 89E. Breit-Wigner mass.
[18] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$.
[19] Reanalysis of ANISOVICH 94 data.
[20] From central value and spread of two solutions. Breit-Wigner mass.

$f_0(1500)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta'(958)$	seen
Γ_2	$\eta\eta$	seen
Γ_3	4π	seen
Γ_4	$4\pi^0$	seen
Γ_5	$2\pi^+2\pi^-$	seen
Γ_6	2π	seen
Γ_7	$\pi^+\pi^-$	seen
Γ_8	$2\pi^0$	seen
Γ_9	$K\overline{K}$	seen

$f_0(1500)$ BRANCHING RATIOS

$\Gamma(\eta\eta'(958))/\Gamma(\eta\eta)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.29±0.10	[21] AMSLER 95C	CBAR	0.0 $\bar{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.84±0.23	ABELE 96C	RVUE	Compilation
2.7 ±0.8	BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$

[21] Using AMSLER 94E ($\eta\eta'\pi^0$).

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
large	ALDE 88	GAM4	300 $\pi^- N \to \eta\eta\pi^- N$
large	BINON 83	GAM2	38 $\pi^- p \to 2\eta n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ Γ_4/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.8±0.3	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(2\pi^0)/\Gamma(\eta\eta)$ Γ_8/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
1.45±0.61	[22] AMSLER 95C	CBAR	0.0 $\bar{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.29±0.72	[23] ABELE 96C	RVUE	Compilation
2.12±0.81	[24] AMSLER 95D	CBAR	0.0 $\bar{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
<0.3	BINON 83	GAM2	38 $\pi^- p \to 2\eta n$

[22] Using AMSLER 95B ($3\pi^0$).

[23] 2π width determined to be 60 ± 12 MeV.

[24] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

$\Gamma(K\overline{K})/\Gamma(\eta\eta)$ Γ_9/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.6		[25] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.4	90	[26] PROKOSHKIN 91	GAM4	300 $\pi^- p \to \pi^- p\eta\eta$

[25] Using ETKIN 82B and COHEN 80.

[26] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production.

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
0.044±0.021	BUGG 96	RVUE

$\Gamma(K\overline{K})/\Gamma(2\pi)$ Γ_9/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
0.19±0.07	[27] ABELE 98	CBAR	0.0 $\bar{p}p \to K^0_L K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.20±0.08	[28] ABELE 96B	CBAR	0.0 $\bar{p}p \to \pi^0 K^0_L K^0_L$

[27] Using $\pi^0\pi^0$ from AMSLER 95B.

[28] Using AMSLER 95B ($3\pi^0$), AMSLER 94C ($2\pi^0\eta$) and SU(3).

$\Gamma(2\pi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
0.454±0.104	BUGG 96	RVUE

$\Gamma(4\pi)/\Gamma(2\pi)$ Γ_3/Γ_6

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.4±0.8	[29] ABELE 96	CBAR	0.0 $\bar{p}p \to 5\pi^0$

[29] Excluding $\rho\rho$ contribution to 4π.

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	BERTIN 98	OBLX	50–405 $\bar{n}p \to \pi^+\pi^+\pi^-$
possibly seen	FRABETTI 97D	E687	$D^\pm_s \to \pi^\mp\pi^\pm\pi^\pm$

$f_0(1500)$ REFERENCES

ABELE 98 PR D57 3860 A. Abele, Adomeit, Amsler+ (Crystal Barrel Collab.)
BERTIN 98 PR D57 55 A. Bertin, Bruschi, Capponi+ (OBELIX Collab.)
BARBERIS 97B PL B413 217 D. Barberis+ (WA102 Collab.)
BERTIN 97C PL B408 476 A. Bertin, Bruschi+ (OBELIX Collab.)
FRABETTI 97D PL B407 79 +Cheung, Cumalat+ (FNAL E687 Collab.)
KAMINSKI 97B PL B413 130 R. Kaminski+ (CRAC, IPN)
ABELE 96 PL B380 453 +Adomeit, Amsler+ (Crystal Barrel Collab.)
ABELE 96B PL B385 425 +Adomeit, Amsler+ (Crystal Barrel Collab.)
ABELE 96C NP A609 562 A. Abele, Adomeit, Armstrong+ (Crystal Barrel Collab.)
AMELIN 96B PAN 59 976 +Berdnikov, Bityukov+ (SERP, TBIL)
Translated from YAF 59 1021.
BUGG 96 NP B471 59 +Sarantsev, Zou (LOQM, PNPI)
AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
ANTINORI 95 PL B353 589 +Barberis, Bayes+ (ATHU, BARI, BIRM, CERN, JINR)
BUGG 95 PL B353 378 +Scott, Zoli+ (LOQM, PNPI, WASH)
ABATZIS 94 PL B324 509 +Antinori, Barberis+ (ATHU, BARI, BIRM, CERN, JINR)
AMSLER 94C PL B327 425 +Armstrong, Ravndal+ (Crystal Barrel Collab.)
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
AMSLER 94E PL B340 259 +Armstrong, Hackman+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
BUGG 94 PR D50 4412 +Anisovich+ (LOQM)
AMSLER 92 PL B291 347 +Augustin, Baker+ (Crystal Barrel Collab.)
BELADIDZE 92C SJNP 55 1535 +Bityukov, Borisov (SERP, TBIL)
Translated from YAF 55 2748.
PROKOSHKIN 91 SPD 36 155 (GAM2, GAM4 Collab.)
Translated from DANS 316 900.
ARMSTRONG 89E PL B228 536 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF, CURIN+)
ALDE 88 PL B201 160 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
BINON 84C NC 80A 363 +Bricman, Donskov+ (BELG, LAPP, SERP, CERN)
BINON 83 NC 78A 313 +Donskov, Duteil+ (BELG, LAPP, SERP, CERN)
Also 83B SJNP 38 561 Binon, Gouanere+ (BELG, LAPP, SERP, CERN)
Translated from YAF 38 934.
GRAY 83 PR D27 307 +Kalogeropoulos, Nandy, Roy, Zenone (SYRA)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
COHEN 80 PR D22 2595 +Ayres, Diebold, Kramer, Pawlicki+ (ANL)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
SRINIVASAN 75 PR D12 681 +Helland, Lennox, Klem+ (NDAM, ANL)

OTHER RELATED PAPERS

ANISOVICH 97 PL B395 123 +Sarantsev (PNPI)
ANISOVICH 97B ZPHY A357 123 A.V. Anisovich+ (PNPI)
ANISOVICH 97C PL B413 137
ANISOVICH 97E PAN 60 1892 A.V. Anisovich+ (PNPI)
Translated from YAF 60 2065.
PROKOSHKIN 97 SPD 42 117 +Kondashov, Sadovsky+ (SERP)
Translated from DANS 353 323.
AMSLER 96 PR D53 295 +Close (ZURI, RAL)
AMSLER 95E PL B353 385 +Close (ZURI, RAL)
GASPERO 95 NP A588 861 (ROMA)
SLAUGHTER 88 MPL A3 1361 (LANL)

$f_1(1510)$

$I^G(J^{PC}) = 0^+(1^{++})$

OMITTED FROM SUMMARY TABLE

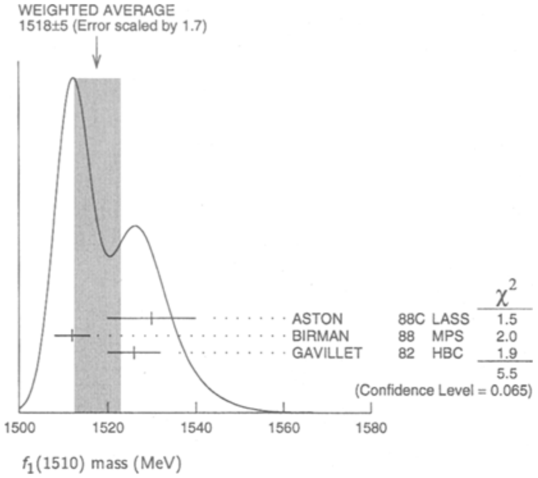
See the minireview under $\eta(1440)$.

$f_1(1510)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1518± 5 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
1530±10		ASTON	88C	LASS	11 $K^- p \to K^0_S K^\pm \pi^\mp \Lambda$
1512± 4	600	[1] BIRMAN	88	MPS	8 $\pi^- p \to K^+ \overline{K}^0 \pi^- n$
1526± 6	271	GAVILLET	82	HBC	4.2 $K^- p \to \Lambda K K \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1525		[2] BAUER	93B		$\gamma\gamma^* \to \pi^+\pi^-\pi^0\pi^0$

[1] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.

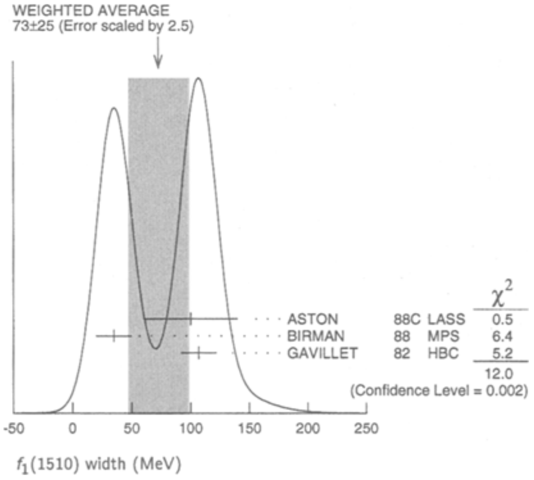
[2] Not seen by AIHARA 88C in the $K^0_S K^\pm \pi^\mp$ final state.



$f_1(1510)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
73±25 OUR AVERAGE		Error includes scale factor of 2.5. See the ideogram below.			
100±40		ASTON	88C	LASS	11 $K^- p \to K^0_S K^\pm \pi^\mp \Lambda$
35±15	600	[3] BIRMAN	88	MPS	8 $\pi^- p \to K^+ \overline{K}^0 \pi^- n$
107±15	271	GAVILLET	82	HBC	4.2 $K^- p \to \Lambda K K \pi$

[3] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.



$f_1(1510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)$+ c.c.	seen

$f_1(1510)$ REFERENCES

BAUER 93B PR D48 3976 +Belcinski, Berg, Bingham+ (SLAC)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
ASTON 88C PL B201 573 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS) JP
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD) JP
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)

OTHER RELATED PAPERS

ABELE 97G PL B415 289 A. Abele+
BARBERIS 97C PL B413 225 D. Barberis+ (WA102 Collab.)
CLOSE 97D ZPHY C76 469 F.E. Close+
KING 91 NP B21 11 (suppl) E. King+ (FSU, BNL+)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
BITYUKOV 84 SJNP 39 735 S. Bityukov+ (SERP)
Translated from YAF 39 1165.

$f_2'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

$f_2'(1525)$ MASS

VALUE (MeV)	DOCUMENT ID
1525±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY PION BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1547^{+10}_{-2}		[1] LONGACRE	86	MPS	22 $\pi^- p \to K^0_S K^0_S n$
1496^{+9}_{-8}		[2] CHABAUD	81	ASPK	6 $\pi^- p \to K^+ K^- n$
1497^{+8}_{-9}		CHABAUD	81	ASPK	18.4 $\pi^- p \to K^+ K^- n$
1492±29		GORLICH	80	ASPK	17 $\pi^- p$ polarized $\to K^+ K^- n$
1502±25		[3] CORDEN	79	OMEG	12–15 $\pi^- p \to \pi^+ \pi^- n$
1480	14	CRENNELL	66	HBC	6.0 $\pi^- p \to K^0_S K^0_S n$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[2] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.

[3] From an amplitude analysis where the $f_2'(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1524.6± 1.4 OUR AVERAGE		Includes data from the datablock that follows this one. Error includes scale factor of 1.1.			
1526.8± 4.3		ASTON	88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
1504 ±12		BOLONKIN	86	SPEC	40 $K^- p \to K^0_S K^0_S Y$
1529 ± 3		ARMSTRONG	83B	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
1521 ± 6	650	AGUILAR-...	81B	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
1521 ± 3	572	ALHARRAN	81	HBC	8.25 $K^- p \to \Lambda K \overline{K}$
1522 ± 6	123	BARREIRO	77	HBC	4.15 $K^- p \to \Lambda K^0_S K^0_S$
1528 ± 7	166	EVANGELISTA	77	OMEG	10 $K^- p \to K^+ K^- (\Lambda, \Sigma)$
1527 ± 3	120	BRANDENB...	76C	ASPK	13 $K^- p \to K^+ K^- (\Lambda, \Sigma)$
1519 ± 7	100	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to K \overline{K} (\Lambda, \Sigma)$

PRODUCED IN e^+e^- ANNIHILATION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1524 ± 4 OUR AVERAGE	Error includes scale factor of 1.2.			
1535 ± 5 ± 4	ABREU	96C	DLPH	$\gamma\gamma \to K^+ K^-$ E^{ee}_{cm}= 91.2 GeV
$1516 \pm 5 {}^{+9}_{-15}$	BAI	96C	BES	$J/\psi \to \gamma K^+ K^-$
1529 ±10	ACCIARRI	95J	L3	$\gamma\gamma \to K^0_S K^0_S$ E^{ee}_{cm}= 88–94 GeV
1531.6±10.0	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
1515 ± 5	[4] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$
1525 ±10 ±10	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1496 ± 2	[5] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$

[4] From an analysis ignoring interference with $f_J(1710)$.

[5] From an analysis including interference with $f_J(1710)$.

$f'_2(1525)$ WIDTH

VALUE (MeV)	DOCUMENT ID	COMMENT
76±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.	
73^{+6}_{-5} OUR FIT		
76±10	PDG 90	For fitting

PRODUCED BY PION BEAM

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
108^{+5}_{-2}	[6] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$
69^{+22}_{-16}	[7] CHABAUD 81	ASPK	$6\ \pi^- p \to K^+ K^- n$
137^{+23}_{-21}	CHABAUD 81	ASPK	$18.4\ \pi^- p \to K^+ K^- n$
150^{+83}_{-50}	GORLICH 80	ASPK	$17\ \pi^- p$polarized $\to K^+ K^- n$
165±42	[8] CORDEN 79	OMEG	$12\text{–}15\ \pi^- p \to \pi^+ \pi^- n$
92^{+39}_{-22}	[9] POLYCHRO... 79	STRC	$7\ \pi^- p \to n K^0_S K^0_S$

[6] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[7] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.

[8] From an amplitude analysis where the $f'_2(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.

[9] From a fit to the D with $f_2(1270)$-$f'_2(1525)$ interference. Mass fixed at 1516 MeV.

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
76± 5 OUR AVERAGE	Includes data from the datablock that follows this one.			
90±12		ASTON 88D	LASS	$11\ K^- p \to K^0_S K^0_S \Lambda$
73±18		BOLONKIN 86	SPEC	$40\ K^- p \to K^0_S K^0_S Y$
83±15		ARMSTRONG 83B	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
85±16	650	AGUILAR-... 81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
80^{+14}_{-11}	572	ALHARRAN 81	HBC	$8.25\ K^- p \to \Lambda K\overline{K}$
72±25	166	EVANGELISTA 77	OMEG	$10\ K^- p \to K^+ K^- (\Lambda, \Sigma)$
69±22	100	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p \to K\overline{K}(\Lambda, \Sigma)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62^{+19}_{-14}	123	BARREIRO 77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
61± 8	120	BRANDENB... 76C	ASPK	$13\ K^- p \to K^+ K^- (\Lambda, \Sigma)$

PRODUCED IN $e^+ e^-$ ANNIHILATION

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
66± 8 OUR AVERAGE			
60±20±19	ABREU 96C	DLPH	$\gamma\gamma \to K^+ K^-$ E^{ee}_{cm}= 91.2 GeV
$60\pm23^{+13}_{-20}$	BAI 96C	BES	$J/\psi \to \gamma K^+ K^-$
103±30	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+ K^-$
62±10	[10] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$
85±35	BALTRUSAIT..87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
76±40	ACCIARRI 95J	L3	$\gamma\gamma \to K_S K_S$ E^{ee}_{cm}= 88–94 GeV
100± 3	[11] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$

[10] From an analysis ignoring interference with $f_J(1710)$.

[11] From an analysis including interference with $f_J(1710)$.

$f'_2(1525)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	(88.8 ±3.1) %
Γ_2	$\eta\eta$	(10.3 ±3.1) %
Γ_3	$\pi\pi$	(8.2 ±1.5) × 10^{-3}
Γ_4	$\gamma\gamma$	(1.32±0.21) × 10^{-6}
Γ_5	$K\overline{K}^*(892)$+ c.c.	
Γ_6	$\pi\pi\eta$	
Γ_7	$\pi K\overline{K}$	
Γ_8	$\pi^+\pi^+\pi^-\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 2 partial widths, a combination of partial widths obtained from integrated cross sections, and 3 branching ratios uses 14 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 = 11.4$ for 10 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta p_i \delta p_j \right\rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cccc}
x_2 & -100 & & & \\
x_3 & -3 & -1 & & \\
x_4 & -7 & 7 & 1 & \\
\Gamma & -32 & 32 & -1 & -42 \\
\hline
 & x_1 & x_2 & x_3 & x_4
\end{array}$$

	Mode	Rate (MeV)
Γ_1	$K\overline{K}$	$65\ ^{+5}_{-4}$
Γ_2	$\eta\eta$	7.6 ±2.6
Γ_3	$\pi\pi$	0.60±0.12
Γ_4	$\gamma\gamma$	(9.7 ±1.4) × 10^{-5}

$f'_2(1525)$ PARTIAL WIDTHS

$\Gamma(K\overline{K})$ Γ_1

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
65^{+5}_{-4} OUR FIT			
63^{+6}_{-5}	[12] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\pi\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.60±0.12 OUR FIT			
$1.4\ ^{+1.0}_{-0.5}$	[12] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\eta\eta)$ Γ_2

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
7.6±2.5 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$24\ ^{+3}_{-1}$	[12] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

[12] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

$f'_2(1525)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\rm total}$ $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.086 ±0.012 OUR FIT			
0.086 ±0.012 OUR AVERAGE			
0.093 ±0.018 ±0.022	[13] ACCIARRI 95J	L3	E^{ee}_{cm}= 88–94 GeV
0.067 ±0.008 ±0.015	[13] ALBRECHT 90G	ARG	$e^+ e^- \to e^+ e^- K^+ K^-$
$0.11\ ^{+0.03}_{-0.02}\ \pm0.02$	BEHREND 89C	CELL	$e^+ e^- \to e^+ e^- K^0_S K^0_S$
$0.10\ ^{+0.04}_{-0.03}\ ^{+0.03}_{-0.02}$	BERGER 88	PLUT	$e^+ e^- \to e^+ e^- K^0_S K^0_S$
0.12 ±0.07 ±0.04	[13] AIHARA 86B	TPC	$e^+ e^- \to e^+ e^- K^+ K^-$
0.11 ±0.02 ±0.04	[13] ALTHOFF 83	TASS	$e^+ e^- \to e^+ e^- K\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0314±0.0050±0.0077	[14] ALBRECHT 90G	ARG	$e^+ e^- \to e^+ e^- K^+ K^-$

[13] Using an incoherent background.

[14] Using a coherent background.

$f'_2(1525)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.12±0.04 OUR FIT			
0.11±0.04	[15] PROKOSHKIN 91	GAM4	$300\ \pi^- p \to \pi^- p \eta\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.50	BARNES 67	HBC	$4.6,5.0\ K^- p$

[15] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$\Gamma(\pi\pi)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.0082±0.0016 OUR FIT				
0.0075±0.0016 OUR AVERAGE				
0.007 ±0.002		COSTA... 80	OMEG	$10\ \pi^- p \to K^+ K^- n$
0.027 $^{+0.071}_{-0.013}$		[16] GORLICH 80	ASPK	$17,18\ \pi^- p$
0.0075±0.0025		[16,17] MARTIN 79	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	95	AGUILAR-... 81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
0.19 ±0.03		CORDEN 79	OMEG	$12–15\ \pi^- p \to \pi^+ \pi^- n$
<0.045	95	BARREIRO 77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
0.012 ±0.004		[16] PAWLICKI 77	SPEC	$6\ \pi N \to K^+ K^- N$
<0.063	90	BRANDENB... 76C	ASPK	$13\ K^- p \to K^+ K^- (\Lambda, \Sigma)$
<0.0086		[16] BEUSCH 75B	OSPK	$8.9\ \pi^- p \to K^0 \overline{K}^0 n$

[16] Assuming that the $f'_2(1525)$ is produced by an one-pion exchange production mechanism.

[17] MARTIN 79 uses the PAWLICKI 77 data with different input value of the $f'_2(1525) \to K\overline{K}$ branching ratio.

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.0092±0.0018 OUR FIT			
0.075 ±0.035	AUGUSTIN 87	DM2	$J/\psi \to \gamma \pi^+ \pi^-$

$\Gamma(\pi\pi\eta)/\Gamma(K\overline{K})$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.41	95	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p$
<0.3	67	AMMAR 67	HBC	

$[\Gamma(K\overline{K}^*(892)+{\rm c.c.})+\Gamma(\pi K\overline{K})]/\Gamma(K\overline{K})$ $(\Gamma_5+\Gamma_7)/\Gamma_1$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.35	95	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p$
<0.4	67	AMMAR 67	HBC	

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K\overline{K})$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.32	95	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p$

$\Gamma(\eta\eta)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.10±0.03	[18] PROKOSHKIN 91	.GAM4	$300\ \pi^- p \to \pi^- p \eta\eta$

[18] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$f'_2(1525)$ REFERENCES

ABREU	96C	PL B379 309	+Adam, Adye+	(DELPHI Collab.)
BAI	96C	PRL 77 3959	J.Z. Bai+	(BES Collab.)
ACCIARRI	95J	PL B363 118	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
PROKOSHKIN	91	SPD 36 155 Translated from DANS 316 900.		(GAM2, GAM4 Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
PDG	90	PL B239	Hernandez, Stone, Porter+	(IFIC, BOST, CIT+)
BEHREND	89C	ZPHY C43 91	+Criegee, Dainton+	(CELLO Collab.)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
BERGER	88	ZPHY C37 329	+Genzel, Lackas+	(PLUTO Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
BOLONKIN	86	SJNP 43 776 Translated from YAF 43 1211.	+Bloshenko+	(ITEP) JP
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, CURIN+)
AGUILAR-...	81B	ZPHY C8 313	Aguilar-Benitez, Albajar+	(CERN, CDEF, MADR+)
ALHARRAN	81	NP B191 26	+Baubillier+	(BIRM, CERN, GLAS, MICH, CURIN)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
BARREIRO	77	NP B121 237	+Diaz, Gay, Hemingway+	(CERN, AMST, NIJM, OXF)
EVANGELISTA	77	NP B127 384	+	(BARI, BONN, CERN, DARE, GLAS+)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL) IJP
BRANDENB...	76C	NP B104 413	Brandenburg, Carnegie, Cashmore+	(SLAC)
BEUSCH	75B	PL 60B 101	+Birman, Websdale, Wetzel	(CERN, ETH)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
AMMAR	67	PRL 19 1071	+Davis, Hwang, Dagan, Derrick+	(NWES, ANL) JP
BARNES	67	PRL 19 964	+Dornan, Goldberg, Leitner+	(BNL, SYRA) IJPC
CRENNELL	66	PRL 16 1025	+Kalbfleisch, Lai, Scarr, Schumann+	(BNL) I

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
ARMSTRONG	82	PL 110B 77	+Baubillier+	(BARI, BIRM, CERN, MILA, CURIN+)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
ABRAMS	67B	PRL 18 620	+Kehoe, Glasser, Sechi-Zorn, Wolsky	(UMD)
BARNES	65	PRL 15 322	+Culwick, Guidoni, Kalbfleisch, Goz+	(BNL, SYRA)

$f_2(1565)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen in antinucleon-nucleon annihilation at rest. See also minireview under non-$q\overline{q}$ candidates. (See the index for the page number.) Needs confirmation.

$f_2(1565)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1542±22 OUR AVERAGE	Error includes scale factor of 2.3. See the ideogram below.		
1575±18	BERTIN 98	OBLX	$50–405\ \bar{n}p \to \pi^+\pi^+\pi^-$
1507±15	[1] BERTIN 97C	OBLX	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
1565±20	MAY 90	ASTE	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1534±20	[2] ABELE 96C	RVUE	Compilation
~ 1552	[3] AMSLER 95D	CBAR	$0.0\ \bar{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
1598±72	BALOSHIN 95	SPEC	$40\ \pi^- {\rm C} \to K^0_S K^0_S X$
1566 $^{+80}_{-50}$	[4] ANISOVICH 94	CBAR	$0.0\ \bar{p}p \to 3\pi^0, \eta\eta\pi^0$
1502± 9	ADAMO 93	OBLX	$\bar{n}p \to \pi^+\pi^+\pi^-$
1488±10	[5] ARMSTRONG 93C	E760	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
1508±10	[5] ARMSTRONG 93D	E760	$\bar{p}p \to 3\pi^0 \to 6\gamma$
1525±10	[5] ARMSTRONG 93D	E760	$\bar{p}p \to \eta\pi^0\pi^0 \to 6\gamma$
~ 1504	[6] WEIDENAUER 93	ASTE	$0.0\ \bar{p}N \to 3\pi^- 2\pi^+$
1540±15	[5] ADAMO 92	OBLX	$\bar{n}p \to \pi^+\pi^+\pi^-$
1515±10	[7] AKER 91	CBAR	$0.0\ \bar{p}p \to 3\pi^0$
1477± 5	BRIDGES 86C	DBC	$0.0\ \bar{p}N \to 3\pi^- 2\pi^+$

[1] T-matrix pole.

[2] T-matrix pole, large coupling to $\rho\rho$ and $\omega\omega$, could be $f_2(1640)$.

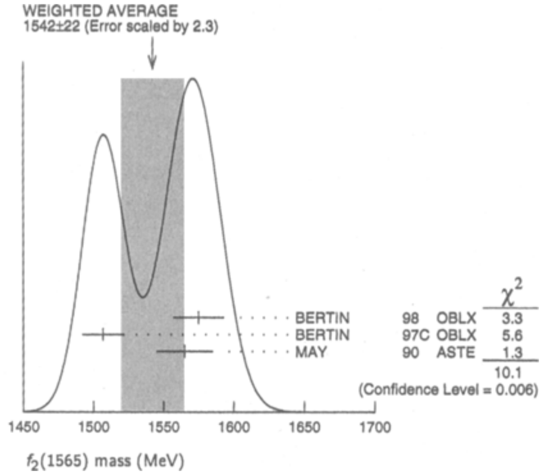
[3] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

[4] From a simultaneous analysis of the annihilations $\bar{p}p \to 3\pi^0, \pi^0\eta\eta$ including AKER 91 data.

[5] J^P not determined, could be partly $f_0(1500)$.

[6] J^P not determined.

[7] Superseded by AMSLER 95B,



$f_2(1565)$ mass (MeV)

$f_2(1565)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
131± 14 OUR AVERAGE			
119± 24	BERTIN 98	OBLX	$50–405\ \bar{n}p \to \pi^+\pi^+\pi^-$
130± 20	[8] BERTIN 97C	OBLX	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
170± 40	MAY 90	ASTE	$0.0\ \bar{p}p \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
180± 60	[9] ABELE 96C	RVUE	Compilation
~ 142	[10] AMSLER 95D	CBAR	$0.0\ \bar{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
263±101	BALOSHIN 95	SPEC	$40\ \pi^- {\rm C} \to K^0_S K^0_S X$
166 $^{+\ 80}_{-\ 20}$	[11] ANISOVICH 94	CBAR	$0.0\ \bar{p}p \to 3\pi^0, \eta\eta\pi^0$
130± 10	[12] ADAMO 93	OBLX	$\bar{n}p \to \pi^+\pi^+\pi^-$
148± 27	[13] ARMSTRONG 93C	E760	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
103± 15	[13] ARMSTRONG 93D	E760	$\bar{p}p \to 3\pi^0 \to 6\gamma$
111± 10	[13] ARMSTRONG 93D	E760	$\bar{p}p \to \eta\pi^0\pi^0 \to 6\gamma$
~ 206	[14] WEIDENAUER 93	ASTE	$0.0\ \bar{p}N \to 3\pi^- 2\pi^+$
132± 37	[13] ADAMO 92	OBLX	$\bar{n}p \to \pi^+\pi^+\pi^-$
120± 10	[15] AKER 91	CBAR	$0.0\ \bar{p}p \to 3\pi^0$
116± 9	BRIDGES 86C	DBC	$0.0\ \bar{p}N \to 3\pi^- 2\pi^+$

[8] T-matrix pole.
[9] T-matrix pole, large coupling to $\rho\rho$ and $\omega\omega$, could be $f_2(1640)$.
[10] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[11] From a simultaneous analysis of the annihilations $\overline{p}p \rightarrow 3\pi^0, \pi^0\eta\eta$ including AKER 91 data.
[12] Supersedes ADAMO 92.
[13] J^P not determined, could be partly $f_0(1500)$.
[14] J^P not determined.
[15] Superseded by AMSLER 95B,

$f_2(1565)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-$	seen
Γ_2	$\pi^0\pi^0$	seen
Γ_3	$\rho^0\rho^0$	seen
Γ_4	$2\pi^+2\pi^-$	seen
Γ_5	$\eta\eta$	seen

$f_2(1565)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BERTIN	98	OBLX	50–405 $\overline{n}p \rightarrow \pi^+\pi^+\pi^-$
not seen	[16] ANISOVICH	94B	RVUE	$\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
seen	MAY	89	ASTE	$\overline{p}p \rightarrow \pi^+\pi^-\pi^0$

[16] ANISOVICH 94B is from a reanalysis of MAY 90.

$\Gamma(\pi^+\pi^-)/\Gamma(\rho^0\rho^0)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.042±0.013	BRIDGES	86B	DBC	$\overline{p}N \rightarrow 3\pi^-2\pi^+$

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMSLER	95B	CBAR	0.0 $\overline{p}p \rightarrow 3\pi^0$

$\Gamma(\eta\eta)/\Gamma(\pi^0\pi^0)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.024±0.005±0.012	[17] ARMSTRONG	93C	E760	$\overline{p}p \rightarrow \pi^0\eta\eta \rightarrow 6\gamma$

[17] J^P not determined, could be partly $f_0(1500)$.

$f_2(1565)$ REFERENCES

BERTIN 98 PR D57 55 A. Bertin, Bruschi, Capponi+ (OBELIX Collab.)
BERTIN 97C PL B408 476 A. Bertin, Bruschi+ (OBELIX Collab.)
ABELE 96C NP A609 562 A. Abele, Adomeit, Armstrong+ (Crystal Barrel Collab.)
AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
BALOSHIN 95 PAN 58 46 +Bolonkin, Vladimirskii+ (ITEP)
Translated from YAF 58 50.
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
ANISOVICH 94B PR D50 1972 +Bugg+ (LOQM)
ADAMO 93 NP A558 13C +Agnello+ (OBELIX Collab.)
ARMSTRONG 93C PL B307 394 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ARMSTRONG 93D PL B307 399 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
ADAMO 92 PL B287 368 +Agnello, Balestra+ (OBELIX Collab.)
AKER 91 PL B260 249 +Amsler, Peters+ (Crystal Barrel Collab.)
MAY 90 ZPHY C46 203 +Duch, Heel+ (ASTERIX Collab.)
MAY 89 PL B225 450 +Duch, Heel+ (ASTERIX Collab.) IJP
BRIDGES 86B PRL 56 215 +Daftari, Kalogeropoulos, Debbe+ (SYRA, CASE)
BRIDGES 86C PRL 57 1534 +Daftari, Kalogeropoulos+ (SYRA)

$\omega(1600)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1649±24 OUR AVERAGE Error includes scale factor of 2.3.						
1609±20	315	[1] ANTONELLI	92	DM2		1.34–2.4$e^+e^- \rightarrow \rho\pi$
1663±12	435	[2] ANTONELLI	92	DM2		1.34–2.4$e^+e^- \rightarrow \omega\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1600±30		[1] CLEGG	94	RVUE		$e^+e^- \rightarrow \rho\pi$
1607±10		[2] CLEGG	94	RVUE		$e^+e^- \rightarrow \omega\pi\pi$
1635±35		[3] CLEGG	94	RVUE		$e^+e^- \rightarrow \rho\pi$
1625±21		[3] CLEGG	94	RVUE		$e^+e^- \rightarrow \omega\pi\pi$
1670±20		ATKINSON	83B	OMEG		20–70 $\gamma p \rightarrow 3\pi X$
1657±13		CORDIER	81	DM1		$e^+e^- \rightarrow \omega 2\pi$
1679±34	21	ESPOSITO	80	FRAM		$e^+e^- \rightarrow 3\pi$
1652±17		COSME	79	OSPK	0	$e^+e^- \rightarrow 3\pi$

[1] From a two Breit-Wigner fit.
[2] From a single Breit-Wigner plus background fit.
[3] From a single Breit-Wigner fit.

$\omega(1600)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
220±35 OUR AVERAGE Error includes scale factor of 1.6.						
159±43	315	[4] ANTONELLI	92	DM2		1.34–2.4$e^+e^- \rightarrow \rho\pi$
240±25	435	[5] ANTONELLI	92	DM2		1.34–2.4$e^+e^- \rightarrow \omega\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
140±50		[4] CLEGG	94	RVUE		$e^+e^- \rightarrow \rho\pi$
86±20		[5] CLEGG	94	RVUE		$e^+e^- \rightarrow \omega\pi\pi$
350±80		[6] CLEGG	94	RVUE		$e^+e^- \rightarrow \rho\pi$
401±63		[6] CLEGG	94	RVUE		$e^+e^- \rightarrow \omega\pi\pi$
160±20		ATKINSON	83B	OMEG		20–70 $\gamma p \rightarrow 3\pi X$
136±46		CORDIER	81	DM1		$e^+e^- \rightarrow \omega 2\pi$
99±49	21	ESPOSITO	80	FRAM		$e^+e^- \rightarrow 3\pi$
42±17		COSME	79	OSPK	0	$e^+e^- \rightarrow 3\pi$

[4] From a two Breit-Wigner fit.
[5] From a single Breit-Wigner plus background fit.
[6] From a single Breit-Wigner fit.

$\omega(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	e^+e^-	seen

$\omega(1600)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
134±14	435	[7] ANTONELLI	92	DM2	1.34–2.4$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
93±27	315	ANTONELLI	92	DM2	1.34–2.4$e^+e^- \rightarrow \rho\pi$
96±35		DONNACHIE	89	RVUE	$e^+e^- \rightarrow \rho\pi$

[7] From a coupled fit of $\rho\pi$ and $\omega\pi\pi$ channels.

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
170±17	435	[8] ANTONELLI	92	DM2	1.34–2.4$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135±16	435	[9] ANTONELLI	92	DM2	1.34–2.4$e^+e^- \rightarrow \omega\pi\pi$
56±31		DONNACHIE	89	RVUE	$e^+e^- \rightarrow \omega 2\pi$

[8] From a coupled fit of $\rho\pi$ and $\omega\pi\pi$ channels.
[9] From a single Breit-Wigner fit.

$\omega(1600)$ REFERENCES

CLEGG 94 ZPHY C62 455 +Donnachie (LANC, MCHS)
ANTONELLI 92 ZPHY C56 15 +Baldini+ (DM2 Collab.)
DONNACHIE 89 ZPHY C42 663 +Clegg (CERN, MCHS)
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSAY)
ESPOSITO 80 LNC 28 195 +Marini, Patteri+ (FRAS, NAPL, PADO, ROMA)
COSME 79 NP B152 215 +Dudelzak, Grelaud, Jean-Marie, Jullian+ (IPN)

OTHER RELATED PAPERS

ACHASOV 97F PAN 60 2029 N.N. Achasov, Kozhevnikov (NOVM)
Translated from YAF 60 2212.
DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, CURIN)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)

$X(1600)$

$I^G(J^{PC}) = 2^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Observed in the reaction $\gamma\gamma \rightarrow \rho\rho$ near threshold. See also minireview under non-$q\overline{q}$ candidates. (See the index for the page number.)

$X(1600)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1600±100	[1] ALBRECHT	91F	ARG	0	$10.2\ e^+e^- \rightarrow e^+e^-2(\pi^+\pi^-)$

[1] Our estimate.

$X(1600)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
400±200	[2] ALBRECHT	91F	ARG	0	$10.2\ e^+e^- \rightarrow e^+e^-2(\pi^+\pi^-)$

[2] Our estimate.

$X(1600)$ REFERENCES

ALBRECHT 91F ZPHY C50 1 +Appuan, Paulini, Funk+ (ARGUS Collab.)

OTHER RELATED PAPERS

BAJC 96 ZPHY A356 187 B. Bajc+
ALBRECHT 89M PL B217 205 +Bockmann+ (ARGUS Collab.)
BEHREND 89D PL B218 494 +Criegee+ (CELLO Collab.)

$f_2(1640)$

$I^G(J^{PC}) = 0^+(2^{++})$

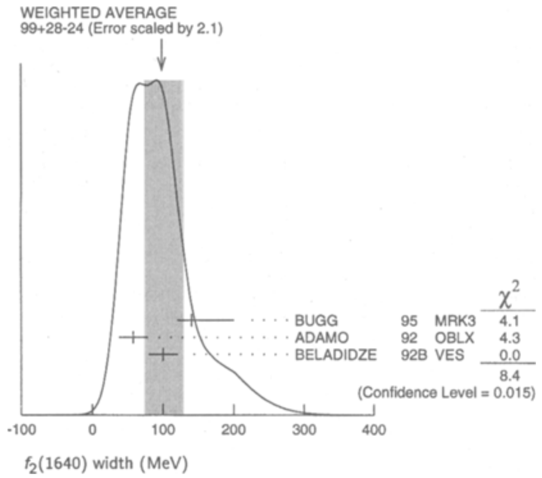
OMITTED FROM SUMMARY TABLE

$f_2(1640)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1638± 6 OUR AVERAGE Error includes scale factor of 1.2.				
1620±16	BUGG	95	MRK3	$J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$
1647± 7	ADAMO	92	OBLX	$\overline{n}p \rightarrow 3\pi^+2\pi^-$
1590±30	BELADIDZE	92B	VES	$36\ \pi^-p \rightarrow \omega\omega n$
1635± 7	ALDE	90	GAM2	$38\ \pi^-p \rightarrow \omega\omega n$

$f_2(1640)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
99^{+28}_{-24} OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.					
140^{+60}_{-20}		BUGG	95	MRK3	$J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$
58±20		ADAMO	92	OBLX	$\overline{n}p \rightarrow 3\pi^+2\pi^-$
100±20		BELADIDZE	92B	VES	$36\ \pi^-p \rightarrow \omega\omega n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 70	90	ALDE	90	GAM2	$38\ \pi^-p \rightarrow \omega\omega n$



$f_2(1640)$ width (MeV)

$f_2(1640)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	seen
Γ_2	4π	seen

$f_2(1640)$ REFERENCES

BUGG 95 PL B353 378 +Scott, Zoli+ (LOQM, PNPI, WASH) JP
ADAMO 92 PL B287 368 +Agnello, Balestra+ (OBELIX Collab.)
BELADIDZE 92B ZPHY C54 367 +Bityukov, Borisov+ (VES Collab.)
ALDE 90 PL B241 600 +Binon+ (SERP, BELG, LANL, LAPP, PISA, KEK)

$\eta_2(1645)$

$I^G(J^{PC}) = 0^+(2^{-+})$

OMITTED FROM SUMMARY TABLE

$\eta_2(1645)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1632±14 OUR AVERAGE					
1620±20	BARBERIS	97B	OMEG		$450\ pp \rightarrow pp2(\pi^+\pi^-)$
1645±14±15	ADOMEIT	96	CBAR	0	$1.94\ \overline{p}p \rightarrow \eta 3\pi^0$

$\eta_2(1645)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
180^{+22}_{-20} OUR AVERAGE					
180±25	BARBERIS	97B	OMEG		$450\ pp \rightarrow pp2(\pi^+\pi^-)$
$180^{+40}_{-21}\pm25$	ADOMEIT	96	CBAR	0	$1.94\ \overline{p}p \rightarrow \eta 3\pi^0$

$\eta_2(1645)$ DECAY MODES

	Mode
Γ_1	$a_2(1320)\pi$
Γ_2	$K\overline{K}\pi$
Γ_3	$K^*\overline{K}$

$\eta_2(1645)$ BRANCHING RATIOS

$\Gamma(K\overline{K}\pi)/\Gamma(a_2(1320)\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.07 ±0.03	[1] BARBERIS	97C	OMEG	$450\ pp \rightarrow ppK\overline{K}\pi$

[1] Using $2(\pi^+\pi^-)$ data from BARBERIS 97B.

$\eta_2(1645)$ REFERENCES

BARBERIS 97B PL B413 217 D. Barberis+ (WA102 Collab.)
BARBERIS 97C PL B413 225 D. Barberis+ (WA102 Collab.)
ADOMEIT 96 ZPHY C71 227 +Amsler, Armstrong+ (Crystal Barrel Collab.)

$X(1650)$

$I^G(J^{PC}) = 0^+(?^{?-})$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

Observed in a study of the $\omega\eta$ effective mass distribution. Needs confirmation.

$X(1650)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1652±7	100	[1] PROKOSHKIN	96	GAM2	0	$32,38\ \pi p \rightarrow \omega\eta n$

[1] Supersedes SAMOILENKO 91.

$X(1650)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<50	90	[2] PROKOSHKIN	96	GAM2	0	$32,38\ \pi p \rightarrow \omega\eta n$

[2] Supersedes SAMOILENKO 91.

$X(1650)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\eta$	seen

$X(1650)$ REFERENCES

PROKOSHKIN 96 SPD 41 247 +Samoilenko (SERP)
Translated from DANS 348 481.
SAMOILENKO 91 SPD 36 473 (SERP)
Translated from DANS 318 1367.

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\omega_3(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1667 ± 4 OUR AVERAGE				
1665.3± 5.2±4.5	23400	AMELIN 96	VES	36 $\pi^- p \to \pi^+\pi^-\pi^0 n$
1685 ±20	60	BAUBILLIER 79	HBC	8.2 $K^- p$ backward
1673 ±12	430	[1,2] BALTAY 78E	HBC	15 $\pi^+ p \to \Delta 3\pi$
1650 ±12		CORDEN 78B	OMEG	8–12 $\pi^- p \to N 3\pi$
1669 ±11	600	[2] WAGNER 75	HBC	7 $\pi^+ p \to \Delta^{++} 3\pi$
1678 ±14	500	DIAZ 74	DBC	6 $\pi^+ n \to p 3\pi^0$
1660 ±13	200	DIAZ 74	DBC	6 $\pi^+ n \to p \omega \pi^0 \pi^0$
1679 ±17	200	MATTHEWS 71D	DBC	7.0 $\pi^+ n \to p 3\pi^0$
1670 ±20		KENYON 69	DBC	8 $\pi^+ n \to p 3\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
~ 1700	110	[1] CERRADA 77B	HBC	4.2 $K^- p \to \Lambda 3\pi$
1695 ±20		BARNES 69B	HBC	4.6 $K^- p \to \omega 2\pi X$
1636 ±20		ARMENISE 68B	DBC	5.1 $\pi^+ n \to p 3\pi^0$

[1] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.

[2] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
168±10 OUR AVERAGE				
149±19±7	23400	AMELIN 96	VES	36 $\pi^- p \to \pi^+\pi^-\pi^0 n$
160±80	60	[3] BAUBILLIER 79	HBC	8.2 $K^- p$ backward
173±16	430	[4,5] BALTAY 78E	HBC	15 $\pi^+ p \to \Delta 3\pi$
253±39		CORDEN 78B	OMEG	8–12 $\pi^- p \to N 3\pi$
173±28	600	[3,5] WAGNER 75	HBC	7 $\pi^+ p \to \Delta^{++} 3\pi$
167±40	500	DIAZ 74	DBC	6 $\pi^+ n \to p 3\pi^0$
122±39	200	DIAZ 74	DBC	6 $\pi^+ n \to p \omega \pi^0 \pi^0$
155±40	200	[3] MATTHEWS 71D	DBC	7.0 $\pi^+ n \to p 3\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
90±20		BARNES 69B	HBC	4.6 $K^- p \to \omega 2\pi$
100±40		KENYON 69	DBC	8 $\pi^+ n \to p 3\pi^0$
112±60		ARMENISE 68B	DBC	5.1 $\pi^+ n \to p 3\pi^0$

[3] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[4] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.

[5] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	$b_1(1235)\pi$	possibly seen

$\omega_3(1670)$ BRANCHING RATIOS

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ **Γ_2/Γ_1**

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.71±0.27	100	DIAZ 74	DBC	6 $\pi^+ n \to p 5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\rho\pi)$ **Γ_3/Γ_1**

VALUE	DOCUMENT ID	TECN	COMMENT
possibly seen	DIAZ 74	DBC	6 $\pi^+ n \to p 5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\omega\pi\pi)$ **Γ_3/Γ_2**

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
>0.75	68	BAUBILLIER 79	HBC	8.2 $K^- p$ backward

$\omega_3(1670)$ REFERENCES

AMELIN 96 ZPHY C70 71 +Berdnikov, Bityukov+ (SERP, TBIL)
BAUBILLIER 79 PL 89B 131 + (BIRM, CERN, GLAS, MSU, ORSAY)
BALTAY 78E PRL 40 87 +Cautis, Kalelkar (COLU) JP
CORDEN 78B NP B138 235 +Corbett, Alexander+ (BIRM, RHEL, TELA, LOWC)
CERRADA 77B NP B126 241 +Blockzijl, Heinen+ (AMST, CERN, NIJM, OXF) JP
WAGNER 75 PL 58B 201 +Tabak, Chew (LBL) JP
DIAZ 74 PRL 32 260 +Dibianca, Fickinger, Anderson+ (CASE, CMU)
MATTHEWS 71D PR D3 2561 +Prentice, Yoon, Carroll+ (TNTO, WISC)
BARNES 69B PRL 23 142 +Chung, Eisner, Flaminio+ (BNL)
KENYON 69 PRL 23 146 +Kinson, Scarr+ (BNL, UCND, ORNL)
ARMENISE 68B PL 26B 336 +Forino, Cartacci+ (BARI, BGNA, FIRZ, ORSAY)

OTHER RELATED PAPERS

MATTHEWS 71 LNC 1 361 +Prentice, Yoon, Carroll+ (TNTO, WISC)
ARMENISE 70 LNC 4 199 +Ghidini, Foring, Cartacci+ (BARI, BGNA, FIRZ)

$\pi_2(1670)$

$I^G(J^{PC}) = 1^-(2^{-+})$

$\pi_2(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1670±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.				
1677± 8 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
1730±20		[1] AMELIN 95B	VES		36 $\pi^- A \to \pi^+\pi^-\pi^- A$
1690±14		[2] BERDNIKOV 94	VES		37 $\pi^- A \to K^+ K^- \pi^- A$
1710±20	700	ANTIPOV 87	SIGM	−	50 π^- Cu $\to \mu^+\mu^-\pi^-$ Cu
1676± 6		[2] EVANGELISTA 81	OMEG	−	12 $\pi^- p \to 3\pi p$
1657±14		[2,3] DAUM 80D	SPEC	−	63–94 $\pi p \to 3\pi X$
1662±10	2000	[2] BALTAY 77	HBC	+	15 $\pi^+ p \to p 3\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

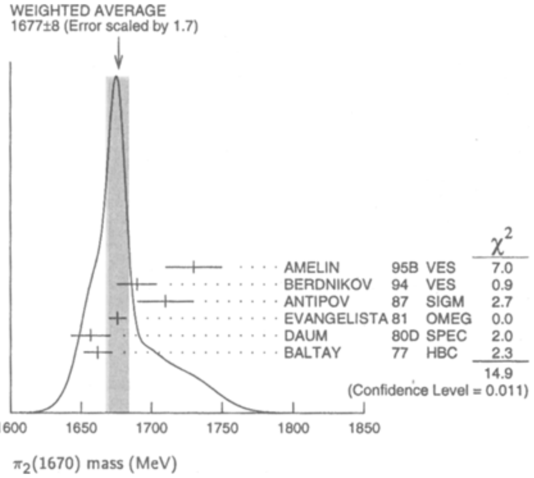
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1742±31±49		ANTREASYAN 90	CBAL		$e^+ e^- \to e^+ e^- \pi^0 \pi^0 \pi^0$
1710±20		[4] DAUM 81B	SPEC	−	63,94 $\pi^- p$
1660±10		[2] ASCOLI 73	HBC	−	5–25 $\pi^- p \to p \pi_2$

[1] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $f_0(1370)\pi$ waves.

[2] From a fit to $J^P = 2^-$ S-wave $f_2(1270)\pi$ partial wave.

[3] Clear phase rotation seen in $2^- S$, $2^- P$, $2^- D$ waves. We quote central value and spread of single-resonance fits to three channels.

[4] From a two-resonance fit to four $2^- 0^+$ waves. This should not be averaged with all the single resonance fits.



$\pi_2(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
258±18 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
310±20		[5] AMELIN 95B	VES		36 $\pi^- A \to \pi^+\pi^-\pi^- A$
190±50		[6] BERDNIKOV 94	VES		37 $\pi^- A \to K^+ K^- \pi^- A$
170±80	700	ANTIPOV 87	SIGM	−	50 π^- Cu $\to \mu^+\mu^-\pi^-$ Cu
260±20		[6] EVANGELISTA 81	OMEG	−	12 $\pi^- p \to 3\pi p$
219±20		[6,7] DAUM 80D	SPEC	−	63–94 $\pi p \to 3\pi X$
285±60	2000	[6] BALTAY 77	HBC	+	15 $\pi^+ p \to p 3\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

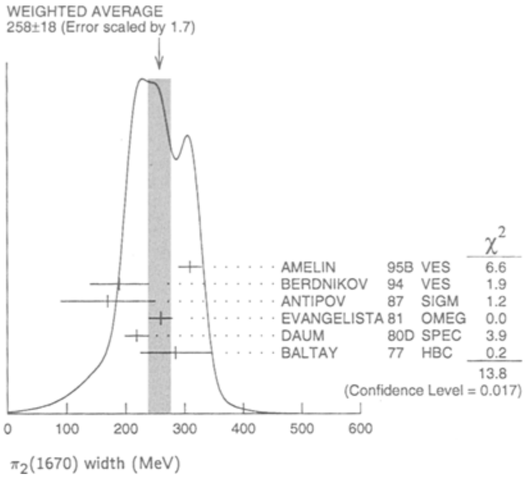
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
236±49±36		ANTREASYAN 90	CBAL		$e^+ e^- \to e^+ e^- \pi^0 \pi^0 \pi^0$
312±50		[8] DAUM 81B	SPEC	−	63,94 $\pi^- p$
270±60		[6] ASCOLI 73	HBC	−	5–25 $\pi^- p \to p \pi_2$

[5] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $f_0(1370)\pi$ waves.

[6] From a fit to $J^P = 2^-$ $f_2(1270)\pi$ partial wave.

[7] Clear phase rotation seen in $2^- S$, $2^- P$, $2^- D$ waves. We quote central value and spread of single-resonance fits to three channels.

[8] From a two-resonance fit to four $2^- 0^+$ waves. This should not be averaged with all the single resonance fits.



$\pi_2(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	(95.8±1.4) %
Γ_2	$f_2(1270)\pi$	(56.2±3.2) %
Γ_3	$\rho\pi$	(31 ±4) %
Γ_4	$f_0(1370)\pi$	(8.7±3.4) %
Γ_5	$K\overline{K}^*(892)$+ c.c.	(4.2±1.4) %
Γ_6	$\gamma\gamma$	
Γ_7	$\eta\pi$	
Γ_8	$\pi^\pm 2\pi^+ 2\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 6 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 1.9 for 3 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−53		
x_4	−29	−59	
x_5	−8	−21	−9
	x_2	x_3	x_4

$\pi_2(1670)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_6

VALUE (keV)	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.072	90	[9] ACCIARRI	97T	L3		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
<0.19	90	[9] ALBRECHT	97B	ARG		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.41 ±0.23±0.28		ANTREASYAN	90	CBAL	0	$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
0.8 ±0.3 ±0.12		[10] BEHREND	90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.3 ±0.3 ±0.2		[11] BEHREND	90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$

[9] Decaying into $f_2(1270)\pi$ and $\rho\pi$.
[10] Constructive interference between $f_2(1270)\pi$,$\rho\pi$ and background.
[11] Incoherent Ansatz.

$\pi_2(1670)$ BRANCHING RATIOS

$\Gamma(3\pi)/\Gamma_{\rm total}$ $\Gamma_1/\Gamma = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	DOCUMENT ID
0.968±0.014 OUR FIT	

$\Gamma(\rho\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\frac{1}{2}\Gamma_3/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.29±0.04 OUR FIT					
0.29±0.05	[12] DAUM	81B	SPEC		63,94 π^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3	BARTSCH	68	HBC	+	$8\ \pi^+p \to 3\pi p$

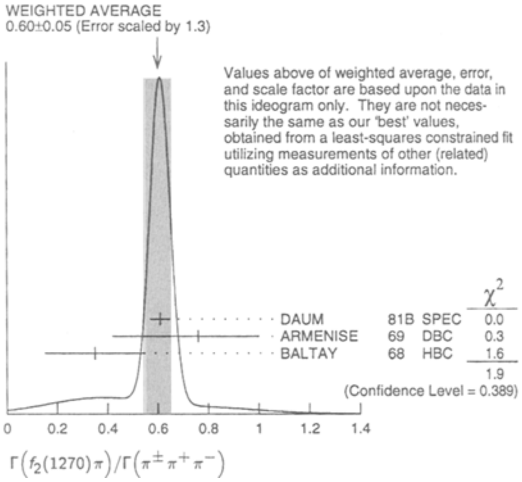
[12] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(f_2(1270)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $0.567\Gamma_2/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(With $f_2(1270) \to \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.604±0.035 OUR FIT					
0.60 ±0.05 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.61 ±0.04	[13] DAUM	81B	SPEC		63,94 π^-p
0.76 $^{+0.24}_{-0.34}$	ARMENISE	69	DBC	+	$5.1\ \pi^+d \to d3\pi$
0.35 ±0.20	BALTAY	68	HBC	+	7–8.5 π^+p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.59	BARTSCH	68	HBC	+	$8\ \pi^+p \to 3\pi p$

[13] From a two-resonance fit to four 2^-0^+ waves.



$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\Gamma_7/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(All η decays.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	BALTAY	68	HBC	+	7–8.5 π^+p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	CRENNELL	70	HBC	−	$6\ \pi^-p \to f_2\pi^-N$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^-)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\Gamma_8/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.10	CRENNELL	70	HBC	−	$6\ \pi^-p \to f_2\pi^-N$
<0.1	BALTAY	68	HBC	+	7,8.5 π^+p

$\Gamma(f_0(1370)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $0.624\Gamma_4/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(With $f_0(1370) \to \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.04 OUR FIT				
0.10±0.05	[14] DAUM	81B	SPEC	63,94 π^-p

[14] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(K\overline{K}^*(892)+{\rm c.c.})/\Gamma(f_2(1270)\pi)$ Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.075±0.025 OUR FIT					
0.075±0.025	[15] ARMSTRONG	82B	OMEG	−	$16\ \pi^-p \to K^+K^-\pi^-p$

[15] From a partial-wave analysis of $K^+K^-\pi^-$ system.

D-wave/*S*-wave RATIO FOR $\pi_2(1670) \to f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.10	[16] DAUM	81B	SPEC	63,94 π^-p

[16] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(1670)$ REFERENCES

ACCIARRI	97T	PL B413 147	M. Acciarri+	
ALBRECHT	97B	ZPHY C74 469	+Hamacher, Hofmann+	(ARGUS Collab.)
AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
BERDNIKOV	94	PL B337 219	+Bityukov+	(SERP, TBIL)
ANTREASYAN	90	ZPHY C48 561	+Bartels, Besset+	(Crystal Ball Collab.)
BEHREND	90C	ZPHY C46 583	+Criegee+	(CELLO Collab.)
ANTIPOV	87	EPL 4 403	+Batarin+	(SERP, JINR, INRM, TBIL, BGNA, MILA)
ARMSTRONG	82B	NP B202 1	+Baccari	(AACH3, BARI, BONN, CERN, GLAS+)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
Also	81B	NP B186 594	Evangelista	
DAUM	80D	PL 89B 285	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY	77	PRL 39 591	+Cautis, Kalelkar	(COLU) JP
ASCOLI	73	PR D7 669		(ILL, TNTO, GENO, HAMB, MILA, SACL) JP
CRENNELL	70	PRL 24 781	+Karshon, Lai, Scarr, Sims	(BNL)
ARMENISE	69	LNC 2 501	+Ghidini, Forino, Cartacci+	(BARI, BGNA, FIRZ)
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
BARTSCH	68	NP B7 345	+Keppel, Kraus+	(AACH, BERL, CERN) JP

OTHER RELATED PAPERS

CHEN 83B PR D28 2304 +Fenker+ (ARIZ, FNAL, FLOR, NDAM, TUFTS+)
LEEDOM 83 PR D27 1426 +DeBonte, Gaidos, Key, Wong+ (PURD, TNTO)
BELLINI 82B NP B199 1 + (CERN, MILA, JINR, BGNA, HELS, PAVI, WARS+)
FOCACCI 66 PRL 17 890 +Kienzle, Levrat, Maglich, Martin (CERN)
LEVRAT 66 PL 22 714 +Tolstrup+ (CERN Missing Mass Spect. Collab.)
VETLITSKY 66 PL 21 579 +Guszavin, Kliger, Zolganov+ (ITEP)
FORINO 65B PL 19 68 +Gessaroli+ (BGNA, BARI, FIRZ, ORSAY, SACL)

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\phi(1680)$ MASS

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1680±20 OUR ESTIMATE				
1681± 8 OUR AVERAGE				
1700±20		[1] CLEGG 94	RVUE	$e^+e^- \rightarrow K^+K^-, K^0_S K\pi$
1657±27	367	BISELLO 91C	DM2	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$
1680±10		[2] BUON 82	DM1	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1655±17		[3] BISELLO 88B	DM2	$e^+e^- \rightarrow K^+K^-$
1677±12		[4] MANE 82	DM1	$e^+e^- \rightarrow K^0_S K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1726±22	BUSENITZ 89	TPS	$\gamma p \rightarrow K^+K^-X$
1760±20	ATKINSON 85C	OMEG	20–70 $\gamma p \rightarrow K\overline{K}X$
1690±10	ASTON 81F	OMEG	25–70 $\gamma p \rightarrow K^+K^-X$

[1] Using BISELLO 88B and MANE 82 data.

[2] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[3] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.

[4] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ WIDTH

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
150±50 OUR ESTIMATE This is only an educated guess; the error given is larger than the error on the average of the published values.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300±60		[5] CLEGG 94	RVUE	$e^+e^- \rightarrow K^+K^-, K^0_S K\pi$
146±55	367	BISELLO 91C	DM2	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$
207±45		[6] BISELLO 88B	DM2	$e^+e^- \rightarrow K^+K^-$
185±22		[7] BUON 82	DM1	$e^+e^- \rightarrow$ hadrons
102±36		[8] MANE 82	DM1	$e^+e^- \rightarrow K^0_S K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
121±47	BUSENITZ 89	TPS	$\gamma p \rightarrow K^+K^-X$
80±40	ATKINSON 85C	OMEG	20–70 $\gamma p \rightarrow K\overline{K}X$
100±40	ASTON 81F	OMEG	25–70 $\gamma p \rightarrow K^+K^-X$

[5] Using BISELLO 88B and MANE 82 data.

[6] From global fit including ρ, ω, ϕ and $\rho(1700)$

[7] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[8] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)+$ c.c.	dominant
Γ_2	$K^0_S K\pi$	seen
Γ_3	$K\overline{K}$	seen
Γ_4	e^+e^-	seen
Γ_5	$\omega\pi\pi$	not seen
Γ_6	$K^+K^-\pi^0$	

$\phi(1680)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel (I) in e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(i)$ or the branching ratio $\Gamma(i)$/total.

$\Gamma(K\overline{K}^*(892)+\text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.48±0.14	367	BISELLO 91C	DM2	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$

$\phi(1680)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K^0_S K\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	MANE 82	DM1	$e^+e^- \rightarrow K^0_S K^\pm\pi^\mp$

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.07 ±0.01	BUON 82	DM1	e^+e^-

$\Gamma(\omega\pi\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ Γ_5/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
<0.10	BUON 82	DM1	e^+e^-

$\phi(1680)$ REFERENCES

CLEGG 94 ZPHY C62 455 +Donnachie (LANC, MCHS)
BISELLO 91C ZPHY C52 227 +Busetto, Castro, Nigro, Pescara+ (DM2 Collab.)
BUSENITZ 89 PR D40 1 +Olszewski, Callahan+ (ILL, FNAL)
BISELLO 88B ZPHY C39 13 +Busetto+ (PADO, CLER, FRAS, LALO)
ATKINSON 85C ZPHY C27 233 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
MANE 82 PL 112B 178 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 81F PL 104B 231 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

OTHER RELATED PAPERS

ACHASOV 97F PAN 60 2029 N.N. Achasov, Kozhevnikov (NOVM)
Translated from YAF 60 2212.
ATKINSON 86C ZPHY C30 541 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 84B NP B231 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSAY)
MANE 81 PL 99B 261 +Bisello, Bizot, Buon, Cordier, Delcourt (ORSAY)
ASTON 80F NP B174 269 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\rho_3(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

$\rho_3(1690)$ MASS

VALUE (MeV)	DOCUMENT ID
1691 ±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1688.8±2.1 OUR AVERAGE	Includes data from the 5 datablocks that follow this one.

2π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1686± 4 OUR AVERAGE					
1677±14		EVANGELISTA 81	OMEG	−	12 $\pi^-p \rightarrow 2\pi p$
1679±11	476	BALTAY 78B	HBC	0	15 $\pi^+p \rightarrow \pi^+\pi^-n$
1678±12	175	[1] ANTIPOV 77	CIBS	0	25 $\pi^-p \rightarrow p3\pi$
1690± 7	600	[1] ENGLER 74	DBC	0	6 $\pi^+n \rightarrow \pi^+\pi^-p$
1693± 8		[2] GRAYER 74	ASPK	0	17 $\pi^-p \rightarrow \pi^+\pi^-n$
1678±12		MATTHEWS 71C	DBC	0	7 π^+N
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1734±10		[3] CORDEN 79	OMEG		12–15 $\pi^-p \rightarrow n2\pi$
1692±12		[2,4] ESTABROOKS 75	RVUE		17 $\pi^-p \rightarrow \pi^+\pi^-n$
1737±23		ARMENISE 70	DBC	0	9 π^+N
1650±35	122	BARTSCH 70B	HBC	+	8 $\pi^+p \rightarrow N2\pi$
1687±21		STUNTEBECK 70	HDBC	0	8 π^-p, 5.4 π^+d
1683±13		ARMENISE 68	DBC	0	5.1 π^+d
1670±30		GOLDBERG 65	HBC	0	6 π^+d, 8 π^-p

[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[2] Uses same data as HYAMS 75.

[3] From a phase shift solution containing a $f'_2(1525)$ width two times larger than the $K\overline{K}$ result.

[4] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1696± 4 OUR AVERAGE						
1699± 5		ALPER	80	CNTR	0	$62\ \pi^- p \to K^+ K^- n$
1698±12	6k	[5,6] MARTIN	78D	SPEC		$10\ \pi p \to K^0_S K^- p$
1692± 6		BLUM	75	ASPK	0	$18.4\ \pi^- p \to n K^+ K^-$
1690±16		ADERHOLZ	69	HBC	+	$8\ \pi^+ p \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694± 8		[7] COSTA...	80	OMEG		$10\ \pi^- p \to K^+ K^- n$

[5] From a fit to $J^P = 3^-$ partial wave.
[6] Systematic error on mass scale subtracted.
[7] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^\pm$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1686± 5 OUR AVERAGE Error includes scale factor of 1.1.						
1694± 6		[8] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to p 4\pi$
1665±15	177	BALTAY	78B	HBC	+	$15\ \pi^+ p \to p 4\pi$
1670±10		THOMPSON	74	HBC	+	$13\ \pi^+ p$
1687±20		CASON	73	HBC	−	$8{,}18.5\ \pi^- p$
1685±14		[9] CASON	73	HBC	−	$8{,}18.5\ \pi^- p$
1680±40	144	BARTSCH	70B	HBC	+	$8\ \pi^+ p \to N 4\pi$
1689±20	102	[9] BARTSCH	70B	HBC	+	$8\ \pi^+ p \to N 2\rho$
1705±21		CASO	70	HBC	−	$11.2\ \pi^- p \to n \rho 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1718±10		[10] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to p 4\pi$
1673± 9		[11] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to p 4\pi$
1733± 9	66	[9] KLIGER	74	HBC	−	$4.5\ \pi^- p \to p 4\pi$
1630±15		HOLMES	72	HBC	+	$10\text{–}12\ K^+ p$
1720±15		BALTAY	68	HBC	+	$7,\ 8.5\ \pi^+ p$

[8] From $\rho^- \rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[9] From $\rho^\pm \rho^0$ mode.
[10] From $a_2(1320)^- \pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[11] From $a_2(1320)^0 \pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1681± 7 OUR AVERAGE					
1670±25	[12] ALDE	95	GAM2		$38\ \pi^- p \to \omega\pi^0 n$
1690±15	EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
1666±14	GESSAROLI	77	HBC		$11\ \pi^- p \to \omega\pi p$
1686± 9	THOMPSON	74	HBC	+	$13\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1654±24	BARNHAM	70	HBC	+	$10\ K^+ p \to \omega\pi X$

[12] Supersedes ALDE 92C.

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

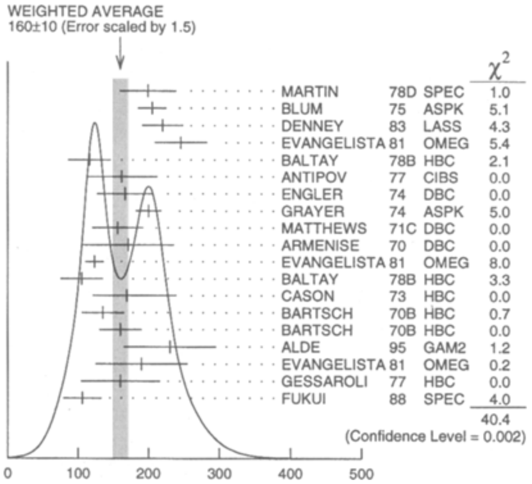
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1680±15	FUKUI	88	SPEC	0	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1700±47	[13] ANDERSON	69	MMS	−	$16\ \pi^- p$ backward
1632±15	[13,14] FOCACCI	66	MMS	−	$7\text{–}12\ \pi^- p \to p\text{MM}$
1700±15	[13,14] FOCACCI	66	MMS	−	$7\text{–}12\ \pi^- p \to p\text{MM}$
1748±15	[13,14] FOCACCI	66	MMS	−	$7\text{–}12\ \pi^- p \to p\text{MM}$

[13] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+ 2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1976)
[14] Not seen by BOWEN 72.

$\rho_3(1690)$ WIDTH

2π, $K\overline{K}$, AND $K\overline{K}\pi$ MODES

VALUE (MeV)	DOCUMENT ID
160±10 OUR AVERAGE Includes data from the 5 datablocks that follow this one. Error includes scale factor of 1.5. See the ideogram below.	

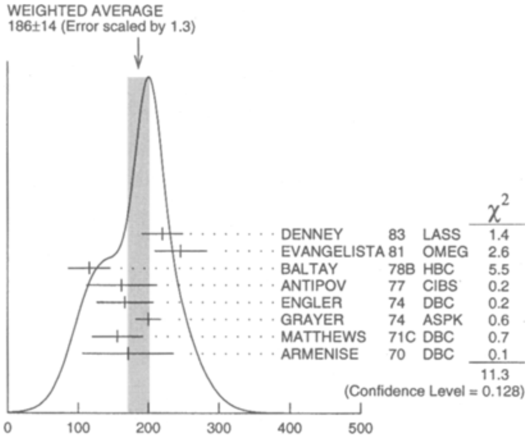


$\rho_3(1690)$ width, 2π, $K\overline{K}$, and $K\overline{K}\pi$ modes (MeV)

2π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
186±14 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.						
220±29		DENNEY	83	LASS		$10\ \pi^+ N$
246±37		EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to 2\pi p$
116±30	476	BALTAY	78B	HBC	0	$15\ \pi^+ p \to \pi^+\pi^- n$
162±50	175	[15] ANTIPOV	77	CIBS	0	$25\ \pi^- p \to p 3\pi$
167±40	600	ENGLER	74	DBC	0	$6\ \pi^+ n \to \pi^+\pi^- p$
200±18		[16] GRAYER	74	ASPK	0	$17\ \pi^- p \to \pi^+\pi^- n$
156±36		MATTHEWS	71C	DBC	0	$7\ \pi^+ N$
171±65		ARMENISE	70	DBC	0	$9\ \pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
322±35		[17] CORDEN	79	OMEG		$12\text{–}15\ \pi^- p \to n 2\pi$
240±30		[16,18] ESTABROOKS	75	RVUE		$17\ \pi^- p \to \pi^+\pi^- n$
180±30	122	BARTSCH	70B	HBC	+	$8\ \pi^+ p \to N 2\pi$
267^{+72}_{-46}		STUNTEBECK	70	HDBC	0	$8\ \pi^- p,\ 5.4\ \pi^+ d$
188±49		ARMENISE	68	DBC	0	$5.1\ \pi^+ d$
180±40		GOLDBERG	65	HBC	0	$6\ \pi^+ d,\ 8\ \pi^- p$

[15] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[16] Uses same data as HYAMS 75 and BECKER 79.
[17] From a phase shift solution containing a $f'_2(1525)$ width two times larger than the $K\overline{K}$ result.
[18] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.



$\rho_3(1690)$ width, 2π mode (MeV)

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
204±18 OUR AVERAGE					
199±40	6000	[19] MARTIN 78D	SPEC		10 $\pi p \rightarrow K^0_S K^- p$
205±20		BLUM 75	ASPK	0	18.4 $\pi^- p \rightarrow n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
219± 4		ALPER 80	CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$
186±11		[20] COSTA... 80	OMEG		10 $\pi^- p \rightarrow K^+ K^- n$
112±60		ADERHOLZ 69	HBC	+	8 $\pi^+ p \rightarrow K\overline{K}\pi$

[19] From a fit to $J^P = 3^-$ partial wave.
[20] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^\pm$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.					
129±10 OUR AVERAGE					
123±13		[21] EVANGELISTA 81	OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
105±30	177	BALTAY 78B	HBC	+	15 $\pi^+ p \rightarrow p 4\pi$
169^{+70}_{-48}		CASON 73	HBC	−	8,18.5 $\pi^- p$
135±30	144	BARTSCH 70B	HBC	+	8 $\pi^+ p \rightarrow N 4\pi$
160±30	102	BARTSCH 70B	HBC	+	8 $\pi^+ p \rightarrow N 2\rho$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
230±28		[22] EVANGELISTA 81	OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
184±33		[23] EVANGELISTA 81	OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
150	66	[24] KLIGER 74	HBC	−	4.5 $\pi^- p \rightarrow p 4\pi$
106±25		THOMPSON 74	HBC	+	13 $\pi^+ p$
125^{+83}_{-35}		[24] CASON 73	HBC	−	8,18.5 $\pi^- p$
130±30		HOLMES 72	HBC	+	10–12 $K^+ p$
180±30	90	[24] BARTSCH 70B	HBC	+	8 $\pi^+ p \rightarrow N a_2 \pi$
100±35		BALTAY 68	HBC	+	7, 8.5 $\pi^+ p$

[21] From $\rho^- \rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[22] From $a_2(1320)^- \pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[23] From $a_2(1320)^0 \pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.
[24] From $\rho^\pm \rho^0$ mode.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.				
190±40 OUR AVERAGE				
230±65	[25] ALDE 95	GAM2		38 $\pi^- p \rightarrow \omega \pi^0 n$
190±65	EVANGELISTA 81	OMEG	−	12 $\pi^- p \rightarrow \omega \pi p$
160±56	GESSAROLI 77	HBC		11 $\pi^- p \rightarrow \omega \pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
89±25	THOMPSON 74	HBC	+	13 $\pi^+ p$
130^{+73}_{-43}	BARNHAM 70	HBC	+	10 $K^+ p \rightarrow \omega \pi X$

[25] Supersedes ALDE 92C.

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.				
106±27	FUKUI 88	SPEC	0	8.95 $\pi^- p \rightarrow \eta \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
195	[26] ANDERSON 69	MMS	−	16 $\pi^- p$ backward
< 21	[26,27] FOCACCI 66	MMS	−	7–12 $\pi^- p \rightarrow p$MM
< 30	[26,27] FOCACCI 66	MMS	−	7–12 $\pi^- p \rightarrow p$MM
< 38	[26,27] FOCACCI 66	MMS	−	7–12 $\pi^- p \rightarrow p$MM

[26] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+ 2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ^0 band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1979)
[27] Not seen by BOWEN 72.

$\rho_3(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	4π	(71.1 ± 1.9) %	
Γ_2	$\pi^\pm \pi^+ \pi^- \pi^0$	(67 ±22) %	
Γ_3	$\omega\pi$	(16 ± 6) %	
Γ_4	$\pi\pi$	(23.6 ± 1.3) %	
Γ_5	$K\overline{K}\pi$	(3.8 ± 1.2) %	
Γ_6	$K\overline{K}$	(1.58± 0.26) %	1.2
Γ_7	$\eta\pi^+\pi^-$	seen	
Γ_8	$\pi\pi\rho$ Excluding 2ρ and $a_2(1320)\pi$.		
Γ_9	$a_2(1320)\pi$		
Γ_{10}	$\rho\rho$		
Γ_{11}	$\phi\pi$		
Γ_{12}	$\eta\pi$		
Γ_{13}	$\pi^\pm 2\pi^+ 2\pi^- \pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 10 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 14.7 for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc}
x_4 & -77 & & \\
x_5 & -74 & 17 & \\
x_6 & -15 & 2 & 0 \\
\hline
 & x_1 & x_4 & x_5
\end{array}$$

$\rho_3(1690)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.236±0.013 OUR FIT				
0.243±0.013 OUR AVERAGE				
$0.259^{+0.018}_{-0.019}$	BECKER 79	ASPK	0	17 $\pi^- p$ polarized
0.23 ±0.02	CORDEN 79	OMEG		12–15 $\pi^- p \rightarrow n 2\pi$
0.22 ±0.04	[28] MATTHEWS 71C	HDBC	0	7 $\pi^+ n \rightarrow \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.245±0.006	[29] ESTABROOKS 75	RVUE		17 $\pi^- p \rightarrow \pi^+ \pi^- n$

[28] One-pion-exchange model used in this estimation.
[29] From phase-shift analysis of HYAMS 75 data.

$\Gamma(\pi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_4/Γ_2

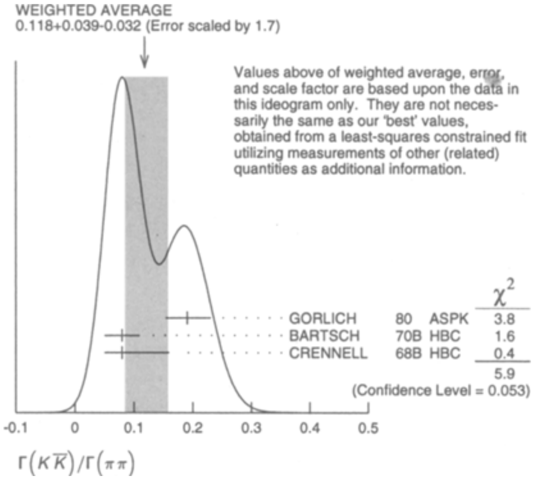
VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.35±0.11	CASON 73	HBC	−	8,18.5 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.2	HOLMES 72	HBC	+	10–12 $K^+ p$
<0.12	BALLAM 71B	HBC	−	16 $\pi^- p$

$\Gamma(\pi\pi)/\Gamma(4\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.332±0.026 OUR FIT Error includes scale factor of 1.1.				
0.30 ±0.10	BALTAY 78B	HBC	0	15 $\pi^+ p \rightarrow p 4\pi$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ — Γ_6/Γ_4

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.067±0.011 OUR FIT Error includes scale factor of 1.2.				
$0.118^{+0.039}_{-0.032}$ OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.			
$0.191^{+0.040}_{-0.037}$	GORLICH 80	ASPK	0	17,18 $\pi^- p$ polarized
0.08 ±0.03	BARTSCH 70B	HBC	+	8 $\pi^+ p$
$0.08^{+0.08}_{-0.03}$	CRENNELL 68B	HBC		6.0 $\pi^- p$



$\Gamma(K\overline{K}\pi)/\Gamma(\pi\pi)$ — Γ_5/Γ_4

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.16±0.05 OUR FIT				
0.16±0.05	[30] BARTSCH 70B	HBC	+	8 $\pi^+ p$

[30] Increased by us to correspond to $B(\rho_3(1690) \to \pi\pi)=0.24$.

$[\Gamma(\pi\pi\rho)+\Gamma(a_2(1320)\pi)+\Gamma(\rho\rho)]/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — $(\Gamma_8+\Gamma_9+\Gamma_{10})/\Gamma_2$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.94±0.09 OUR AVERAGE				
0.96±0.21	BALTAY 78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.88±0.15	BALLAM 71B	HBC	−	16 $\pi^- p$
1 ±0.15	BARTSCH 70B	HBC	+	8 $\pi^+ p$
consistent with 1	CASO 68	HBC	−	11 $\pi^- p$

$\Gamma(\rho\rho)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{10}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.12±0.11		BALTAY 78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.56	66	KLIGER 74	HBC	−	4.5 $\pi^- p \to p4\pi$
0.13±0.09		[31] THOMPSON 74	HBC	+	13 $\pi^+ p$
0.7 ±0.15		BARTSCH 70B	HBC	+	8 $\pi^+ p$

[31] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\rho\rho)/[\Gamma(\pi\pi\rho)+\Gamma(a_2(1320)\pi)+\Gamma(\rho\rho)]$ — $\Gamma_{10}/(\Gamma_8+\Gamma_9+\Gamma_{10})$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.48±0.16	CASO 68	HBC	−	11 $\pi^- p$

$\Gamma(a_2(1320)\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_9/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.66±0.08	BALTAY 78B	HBC	+	15 $\pi^+ p \to p4\pi$
0.36±0.14	[32] THOMPSON 74	HBC	+	13 $\pi^+ p$
not seen	CASON 73	HBC	−	8,18.5 $\pi^- p$
0.6 ±0.15	BARTSCH 70B	HBC	+	8 $\pi^+ p$
0.6	BALTAY 68	HBC	+	7,8.5 $\pi^+ p$

[32] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\omega\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
0.23±0.05 OUR AVERAGE Error includes scale factor of 1.2.					
0.33±0.07		THOMPSON 74	HBC	+	13 $\pi^+ p$
0.12±0.07		BALLAM 71B	HBC	−	16 $\pi^- p$
0.25±0.10		BALTAY 68	HBC	+	7,8.5 $\pi^+ p$
0.25±0.10		JOHNSTON 68	HBC	−	7.0 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	95	BALTAY 78B	HBC	+	15 $\pi^+ p \to p4\pi$
<0.09		KLIGER 74	HBC	−	4.5 $\pi^- p \to p4\pi$

$\Gamma(\phi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{11}/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.11	BALTAY 68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^- \pi^0)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{13}/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.15	BALTAY 68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{12}/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	THOMPSON 74	HBC	+	13 $\pi^+ p$

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.0158±0.0026 OUR FIT Error includes scale factor of 1.2.				
0.0130±0.0024 OUR AVERAGE				
0.013 ±0.003	COSTA... 80	OMEG	0	10 $\pi^- p \to K^+ K^- n$
0.013 ±0.004	[33] MARTIN 78B	SPEC	−	10 $\pi p \to K^0_S K^- p$

[33] From $(\Gamma_4\Gamma_6)^{1/2} = 0.056 \pm 0.034$ assuming $B(\rho_3(1690) \to \pi\pi) = 0.24$.

$\Gamma(\omega\pi)/[\Gamma(\omega\pi)+\Gamma(\rho\rho)]$ — $\Gamma_3/(\Gamma_3+\Gamma_{10})$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.08	CASON 73	HBC	−	8,18.5 $\pi^- p$

$\Gamma(\eta\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	FUKUI 88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\rho_3(1690)$ REFERENCES

ALDE	95	ZPHY C66 379	+Binon, Bricman+	(GAMS Collab.)	JP
ALDE	92C	ZPHY C54 553	+Bencheikh, Binon+	(BELG, SERP, KEK, LANL, LAPP)	
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)	
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)	
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)	
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)	
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)	
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)	
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)	
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)	JP
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)	
MARTIN	78B	NP B140 158	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)	
MARTIN	78D	PL 74B 417	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)	
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)	
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)	
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM)	JP
ESTABROOKS	75	NP B95 322	+Martin	(DURH)	
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)	
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)	
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)	
KLIGER	74	SJNP 19 428	+Beketov, Grechko, Guzhavin, Dubovikov+	(ITEP)	
		Translated from YAF 19 839.			
OREN	74	NP B71 189	+Cooper, Fields, Rhines, Allison+	(ANL, OXF)	
THOMPSON	74	NP B69 220	+Gaidos, Mcllwain, Miller, Mulera+	(PURD)	
CASON	73	PR D7 1971	+Biswas, Kenney, Madden+	(NDAM)	
BOWEN	72	PRL 29 890	+Earles, Faissler, Blieden+	(NEAS, STON)	
HOLMES	72	PR D6 3336	+Ferbel, Slattery, Werner	(ROCH)	
BALLAM	71B	PR D3 2606	+Chadwick, Guiragossian, Johnson+	(SLAC)	
MATTHEWS	71C	NP B33 1	+Prentice, Yoon, Carroll+	(TNTO, WISC)	JP
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)	
BARNHAM	70	PRL 24 1083	+Colley, Jobes, Kenyon, Pathak, Riddiford	(BIRM)	
BARTSCH	70B	NP B22 109	+Kraus, Tsanos, Grote+	(AACH, BERL, CERN)	
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)	
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+	(NDAM)	
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH3, BERL, CERN, JAGL, WARS)	
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)	
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSAY)	I
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE)	I
CASO	68	NC 54A 983	+Conte, Cords, Diaz+	(GENO, HAMB, MILA, SACL)	
CRENNELL	68B	PL 28B 136	+Karshon, Lai, Scarr, Skillicorn	(BNL)	
JOHNSTON	68	PRL 20 1414	+Prentice, Steenberg, Yoon	(TNTO, WISC)	IJP
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)	
GOLDBERG	65	PL 17 354	+	(CERN, EPOL, ORSAY, MILA, CEA, SACL)	

OTHER RELATED PAPERS

BARNETT	83B	PL 120B 455	+Blockus, Burka, Chien, Christian+	(JHU)
EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
SEGUINOT	66	PL 19 712	+Martin+	(CERN Missing Mass Spect. Collab.)
BELLINI	65	NC 40A 948	+DiCorato, Duimio, Fiorini	(MILA)
DEUTSCH...	65	PL 18 351	Deutschmann+	(AACH3, BERL, CERN)
FORINO	65	PL 19 65	+Gessaroli+	(BGNA, ORSAY, SACL)

$\rho(1700)$

$I^G(J^{PC}) = 1^+(1^{--})$

THE $\rho(1450)$ AND THE $\rho(1700)$

Written March 1998 by S. Eidelman (Novosibirsk) and J. Hernandez (Valencia).

In our 1988 edition, we replaced the $\rho(1600)$ entry with two new ones, the $\rho(1450)$ and the $\rho(1700)$, because there was emerging evidence that the 1600-MeV region actually contains two ρ-like resonances. ERKAL 86 had pointed out this possibility with a theoretical analysis on the consistency of 2π and 4π electromagnetic form factors and the $\pi\pi$ scattering length. DONNACHIE 87, with a full analysis of data on the 2π and 4π final states in e^+e^- annihilation and photoproduction reactions, had also argued that in order to obtain a consistent picture two resonances were necessary. The existence of $\rho(1450)$ was supported by the analysis of $\eta\rho^0$ mass spectra obtained in photoproduction and e^+e^- annihilation (DONNACHIE 87B) as well as that of $e^+e^- \to \omega\pi$ (DONNACHIE 91).

The analysis of DONNACHIE 87 was further extended by CLEGG 88, 94 to include new data on 4π systems produced in e^+e^- annihilation and in τ decays (τ decays to 4π and e^+e^- annihilation to 4π can be related by the Conserved Vector Current assumption). These systems were successfully analyzed using interfering contributions from two ρ-like states, and from the tail of the $\rho(770)$ decaying into two-body states. While specific conclusions on $\rho(1450) \to 4\pi$ were obtained, little could be said about the $\rho(1700)$.

An analysis by CLEGG 90 of 6π mass spectra from e^+e^- annihilation and from diffractive photoproduction provides evidence for two ρ mesons at about 2.1 and 1.8 GeV that decay strongly into 6π states. While the former is a candidate for a new resonance ($\rho(2150)$), the latter could be a manifestation of the $\rho(1700)$ distorted by threshold effects.

Independent evidence for two 1^- states is provided by KILLIAN 80 in 4π electroproduction at $\langle Q^2 \rangle = 1$ (GeV/c)^2, and by FUKUI 88 in a high-statistics sample of the $\eta\pi\pi$ system in $\pi^- p$ charge exchange.

This scenario with two overlapping resonances is supported by other data. BISELLO 89 measured the pion form factor in the interval 1.35–2.4 GeV and observed a deep minimum around 1.6 GeV. The best fit was obtained with the hypothesis of ρ-like resonances at 1420 and 1770 MeV with widths of about 250 MeV. ANTONELLI 88 found that the $e^+e^- \to \eta\pi^+\pi^-$ cross section is better fitted with two fully interfering Breit-Wigners, with parameters in fair agreement with those of DONNACHIE 87 and BISELLO 89. These results can be considered as a confirmation of the $\rho(1450)$.

Decisive evidence for the $\pi\pi$ decay mode of both $\rho(1450)$ and $\rho(1700)$ came from recent results in $\bar{p}p$ annihilation at rest (ABELE 97). According to ABELE 98 these resonances also possess a $K\overline{K}$ decay mode. High statistics studies of the $\tau \to \pi\pi\nu_\tau$ decay also require the $\rho(1450)$ (BARATE 97M, URHEIM 97), but are not sensitive to the $\rho(1700)$ because it is too close to the τ mass.

The structure of these ρ states is not yet completely clear. BARNES 97 and CLOSE 97C claim that $\rho(1450)$ has a mass consistent with radial $2S$, but its decays show characteristics of hybrids and suggest that this state may be a $2S$-hybrid mixture.

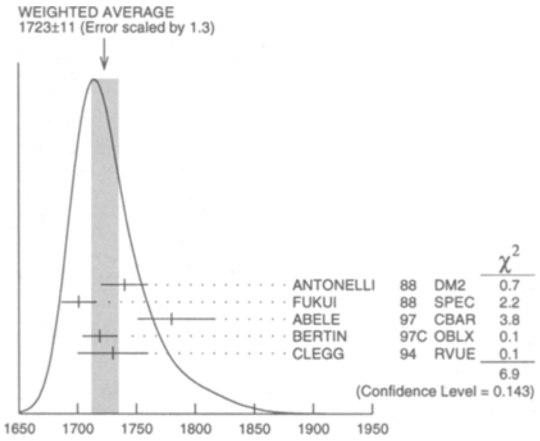
We also list under the $\rho(1450)$ the $\phi\pi$ state with $J^{PC} = 1^{--}$ or $C(1480)$ observed by BITYUKOV 87. While ACHASOV 96B shows that it may be a threshold effect, CLEGG 88 and LANDSBERG 92 suggest two independent vector states with this decay mode. Note, however, that $C(1480)$ in its $\phi\pi$ decay mode was not confirmed by e^+e^- (DOLINSKY 91, BISELLO 91C) and $\bar{p}p$ (ABELE 97H) experiments.

Several observations on the $\omega\pi$ system in the 1200-MeV region (FRENKIEL 72, COSME 76, BARBER 80C, ASTON 80C, ATKINSON 84C, BRAU 88, AMSLER 93B) may be interpreted in terms of either $J^P = 1^-$ $\rho(770) \to \omega\pi$ production (LAYSSAC 71) or $J^P = 1^+$ $b_1(1235)$ production (BRAU 88, AMSLER 93B). We argue that no special entry for a $\rho(1250)$ is needed. The LASS amplitude analysis (ASTON 91B) showing evidence for $\rho(1270)$ is preliminary and needs confirmation. For completeness, the relevant observations are listed under the $\rho(1450)$.

$\rho(1700)$ MASS

$\eta\rho^0$ AND $\pi^+\pi^-$ MODES

VALUE (MeV)	DOCUMENT ID
1700±20 OUR ESTIMATE	
1723±11 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.3. See the ideogram below.



$\rho(1700)$ mass, $\eta\rho^0$ and $\pi^+\pi^-$ modes (MeV)

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1740±20	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1701±15	[1] FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1780 $^{+37}_{-29}$	[2] ABELE	97	CBAR	$\bar{p}n \to \pi^-\pi^0\pi^0$
1719 ±15	[2] BERTIN	97C	OBLX	0.0 $\bar{p}p \to \pi^+\pi^-\pi^0$
1730 ±30	CLEGG	94	RVUE	$e^+e^- \to \pi^+\pi^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

1768 ±21	BISELLO	89	DM2	$e^+e^- \rightarrow \pi^+\pi^-$
1745.7±91.9	DUBNICKA	89	RVUE	$e^+e^- \rightarrow \pi^+\pi^-$
1546 ±26	GESHKEN...	89	RVUE	
1650	[3] ERKAL	85	RVUE	20–70 $\gamma p \rightarrow \gamma\pi$
1550 ±70	ABE	84B	HYBR	20 $\gamma p \rightarrow \pi^+\pi^- p$
1590 ±20	[4] ASTON	80	OMEG	20–70 $\gamma p \rightarrow p2\pi$
1600 ±10	[5] ATIYA	79B	SPEC	50 $\gamma C \rightarrow C2\pi$
1598 $^{+24}_{-22}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
1659 ±25	[3] LANG	79	RVUE	
1575	[3] MARTIN	78C	RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
1610 ±30	[3] FROGGATT	77	RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
1590 ±20	[6] HYAMS	73	ASPK	17 $\pi^- p \rightarrow \pi^+\pi^- n$

$\pi\omega$ MODE

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1710±90	ACHASOV	97	RVUE	$e^+e^- \rightarrow \omega\pi^0$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1582±36	1600	CLELAND	82B SPEC	±	50 $\pi p \rightarrow K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1851$^{+27}_{-24}$		ACHASOV	97 RVUE	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
1570± 20		[7] CORDIER	82 DM1	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
1520± 30		[4] ASTON	81E OMEG	20–70 $\gamma p \rightarrow p4\pi$
1654± 25		[8] DIBIANCA	81 DBC	$\pi^+ d \rightarrow pp2(\pi^+\pi^-)$
1666± 39		[7] BACCI	80 FRAG	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
1780	34	KILLIAN	80 SPEC	11 $e^- p \rightarrow 2(\pi^+\pi^-)$
1500		[9] ATIYA	79B SPEC	50 $\gamma C \rightarrow C4\pi^\pm$
1570± 60	65	[10] ALEXANDER	75 HBC	7.5 $\gamma p \rightarrow p4\pi$
1550± 60		[4] CONVERSI	74 OSPK	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
1550± 50	160	SCHACHT	74 STRC	5.5–9 $\gamma p \rightarrow p4\pi$
1450±100	340	SCHACHT	74 STRC	9–18 $\gamma p \rightarrow p4\pi$
1430± 50	400	BINGHAM	72B HBC	9.3 $\gamma p \rightarrow p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1660±30	ATKINSON	85B OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1783±15	CLEGG	90 RVUE	$e^+e^- \rightarrow 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[1] Assuming $\rho^+ f_0(1370)$ decay mode interferes with $a_1(1260)^+\pi$ background. From a two Breit-Wigner fit.

[2] T-matrix pole.

[3] From phase shift analysis of HYAMS 73 data.

[4] Simple relativistic Breit-Wigner fit with constant width.

[5] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.

[6] Included in BECKER 79 analysis.

[7] Simple relativistic Breit-Wigner fit with model dependent width.

[8] One peak fit result.

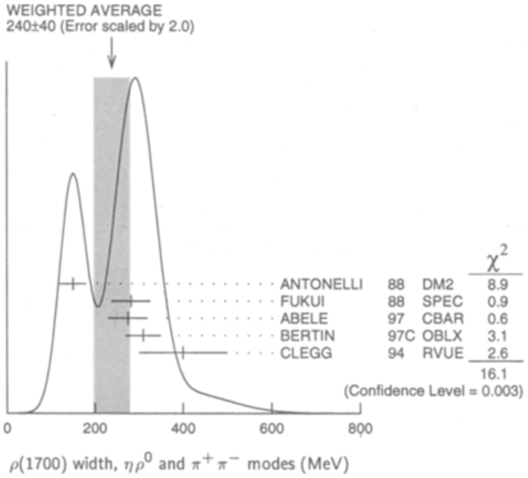
[9] Parameters roughly estimated, not from a fit.

[10] Skew mass distribution compensated by Ross-Stodolsky factor.

$\rho(1700)$ WIDTH

$\eta\rho^0$ AND $\pi^+\pi^-$ MODES

VALUE (MeV)	DOCUMENT ID
240±60 OUR ESTIMATE	
240±40 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 2.0. See the ideogram below.



$\rho(1700)$ width, $\eta\rho^0$ and $\pi^+\pi^-$ modes (MeV)

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
150±30	ANTONELLI	88 DM2	$e^+e^- \rightarrow \eta\pi^+\pi^-$
282±44	[11] FUKUI	88 SPEC	8.95 $\pi^- p \rightarrow \eta\pi^+\pi^- n$

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
275 ± 45	[12] ABELE	97 CBAR	$\overline{p}n \rightarrow \pi^-\pi^0\pi^0$
310 ± 40	[12] BERTIN	97C OBLX	0.0 $\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
400 ±100	CLEGG	94 RVUE	$e^+e^- \rightarrow \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
224 ± 22	BISELLO	89 DM2	$e^+e^- \rightarrow \pi^+\pi^-$
242.5±163.0	DUBNICKA	89 RVUE	$e^+e^- \rightarrow \pi^+\pi^-$
620 ± 60	GESHKEN...	89 RVUE	
<315	[13] ERKAL	85 RVUE	20–70 $\gamma p \rightarrow \gamma\pi$
280 $^{+30}_{-80}$	ABE	84B HYBR	20 $\gamma p \rightarrow \pi^+\pi^- p$
230 ± 80	[14] ASTON	80 OMEG	20–70 $\gamma p \rightarrow p2\pi$
283 ± 14	[15] ATIYA	79B SPEC	50 $\gamma C \rightarrow C2\pi$
175 $^{+98}_{-53}$	BECKER	79 ASPK	17 $\pi^- p$ polarized
232 ± 34	[13] LANG	79 RVUE	
340	[13] MARTIN	78C RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
300 ±100	[13] FROGGATT	77 RVUE	17 $\pi^- p \rightarrow \pi^+\pi^- n$
180 ± 50	[16] HYAMS	73 ASPK	17 $\pi^- p \rightarrow \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
265±120	1600	CLELAND	82B SPEC	±	50 $\pi p \rightarrow K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
510± 40		[17] CORDIER	82 DM1	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
400± 50		[14] ASTON	81E OMEG	20–70 $\gamma p \rightarrow p4\pi$
400±146		[18] DIBIANCA	81 DBC	$\pi^+ d \rightarrow pp2(\pi^+\pi^-)$
700±160		[17] BACCI	80 FRAG	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
100	34	KILLIAN	80 SPEC	11 $e^- p \rightarrow 2(\pi^+\pi^-)$
600		[19] ATIYA	79B SPEC	50 $\gamma C \rightarrow C4\pi^\pm$
340±160	65	[20] ALEXANDER	75 HBC	7.5 $\gamma p \rightarrow p4\pi$
360±100		[14] CONVERSI	74 OSPK	$e^+e^- \rightarrow 2(\pi^+\pi^-)$
400±120	160	[21] SCHACHT	74 STRC	5.5–9 $\gamma p \rightarrow p4\pi$
850±200	340	[21] SCHACHT	74 STRC	9–18 $\gamma p \rightarrow p4\pi$
650±100	400	BINGHAM	72B HBC	9.3 $\gamma p \rightarrow p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
300±50	ATKINSON	85B OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
285 ± 20	CLEGG	90	RVUE	$e^+e^- \to 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[11] Assuming $\rho^+ f_0(1370)$ decay mode interferes with $a_1(1260)^+\pi$ background. From a two Breit-Wigner fit.

[12] T-matrix pole.

[13] From phase shift analysis of HYAMS 73 data.

[14] Simple relativistic Breit-Wigner fit with constant width.

[15] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.

[16] Included in BECKER 79 analysis.

[17] Simple relativistic Breit-Wigner fit with model-dependent width.

[18] One peak fit result.

[19] Parameters roughly estimated, not from a fit.

[20] Skew mass distribution compensated by Ross-Stodolsky factor.

[21] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\rho(1700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi\pi$	dominant
Γ_2	$2(\pi^+\pi^-)$	large
Γ_3	$\rho^0\pi^+\pi^-$	large
Γ_4	$\rho^0\pi^0\pi^0$	
Γ_5	$\rho^\pm\pi^\mp\pi^0$	large
Γ_6	$\pi^+\pi^-$	seen
Γ_7	$\pi^-\pi^0$	seen
Γ_8	$K\overline{K}^*(892)+$ c.c.	seen
Γ_9	$\eta\rho$	seen
Γ_{10}	$K\overline{K}$	seen
Γ_{11}	e^+e^-	seen
Γ_{12}	$\pi^0\omega$	seen

$\rho(1700)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the cross-section into channel$_i$ in e^+e^- annihilation.

$\Gamma(2(\pi^+\pi^-)) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_2\Gamma_{11}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.83 ± 0.42	BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$2.6\ \pm0.2$	DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$

$\Gamma(\pi^+\pi^-) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_6\Gamma_{11}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13	[22] DIEKMAN	88	RVUE	$e^+e^- \to \pi^+\pi^-$

[22] Using total width = 220 MeV.

$\Gamma(K\overline{K}^*(892)+\text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_8\Gamma_{11}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.305 ± 0.071	[23] BIZOT	80	DM1'	e^+e^-

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_9\Gamma_{11}/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
$7\ \pm3$	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_{10}\Gamma_{11}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035 ± 0.029	[23] BIZOT	80	DM1	e^+e^-

$\Gamma(\rho\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_{11}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.510 ± 0.090	[23] BIZOT	80	DM1	e^+e^-

[23] Model dependent.

$\rho(1700)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.287^{+0.043}_{-0.042}$	BECKER	79	ASPK	17 π^-p polarized
0.15 to 0.30	[24] MARTIN	78C	RVUE	17 $\pi^-p \to \pi^+\pi^-n$
<0.20	[25] COSTA...	77B	RVUE	$e^+e^- \to 2\pi,\ 4\pi$
$0.30\ \pm0.05$	[24] FROGGATT	77	RVUE	17 $\pi^-p \to \pi^+\pi^-n$
<0.15	[26] EISENBERG	73	HBC	5 $\pi^+p \to \Delta^{++}2\pi$
$0.25\ \pm0.05$	[27] HYAMS	73	ASPK	17 $\pi^-p \to \pi^+\pi^-n$

[24] From phase shift analysis of HYAMS 73 data.

[25] Estimate using unitarity, time reversal invariance, Breit-Wigner.

[26] Estimated using one-pion-exchange model.

[27] Included in BECKER 79 analysis.

$\Gamma(\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13 ± 0.05	ASTON	80	OMEG	20–70 $\gamma p \to p2\pi$
<0.14	[28] DAVIER	73	STRC	6–18 $\gamma p \to p4\pi$
<0.2	[29] BINGHAM	72B	HBC	9.3 $\gamma p \to p2\pi$

[28] Upper limit is estimate.

[29] 2σ upper limit.

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(2(\pi^+\pi^-))$ — Γ_8/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15 ± 0.03	[30] DELCOURT	81B	DM1	$e^+e^- \to \overline{K}K\pi$

[30] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04		DONNACHIE	87B	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	58	ATKINSON	86B	OMEG	20–70 γp

$\Gamma(\eta\rho)/\Gamma(2(\pi^+\pi^-))$ — Γ_9/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.123 ± 0.027	DELCOURT	82	DM1	$e^+e^- \to \pi^+\pi^-$ MM
~ 0.1	ASTON	80	OMEG	20–70 γp

$\Gamma(\pi^+\pi^-\ \text{neutrals})/\Gamma(2(\pi^+\pi^-))$ — $(\Gamma_4+\Gamma_5+0.714\Gamma_9)/\Gamma_2$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6 ± 0.4	[31] BALLAM	74	HBC	9.3 γp

[31] Upper limit. Background not subtracted.

$\Gamma(\pi^0\omega)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ACHASOV	97	RVUE	$e^+e^- \to \omega\pi^0$

$\Gamma(K\overline{K})/\Gamma(2(\pi^+\pi^-))$ — Γ_{10}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.015 ± 0.010		[32] DELCOURT	81B	DM1		$e^+e^- \to \overline{K}K$
<0.04	95	BINGHAM	72B	HBC	0	9.3 γp

[32] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_{10}/Γ_8

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052 ± 0.026	BUON	82	DM1	$e^+e^- \to$ hadrons

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_3/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1.0		DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
$0.7\ \pm0.1$	500	SCHACHT	74	STRC	5.5–18 $\gamma p \to p4\pi$
0.80		[33] BINGHAM	72B	HBC	9.3 $\gamma p \to p4\pi$

[33] The $\pi\pi$ system is in S-wave.

$\Gamma(\rho^0\pi^0\pi^0)/\Gamma(\rho^\pm\pi^\mp\pi^0)$ — Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	ATKINSON	85B	OMEG		20–70 γp
<0.15	ATKINSON	82	OMEG	0	20–70 $\gamma p \to p4\pi$

ρ(1700) REFERENCES

ABELE	97	PL B391 191	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
ACHASOV	97	PR D55 2663	+Kozhevnikov+	(NOVM)
BERTIN	97C	PL B408 476	A. Bertin, Bruschi+	(OBELIX Collab.)
CLEGG	94	ZPHY C62 455	+Donnachie	(LANC, MCHS)
CLEGG	90	ZPHY C45 677	+Donnachie	(LANC, MCHS)
BISELLO	89	PL B220 321	+Busetto+	(DM2 Collab.)
DUBNICKA	89	JPG 15 1349	+Martinovic+	(JINR, SLOV)
GESHKEN...	89	ZPHY 45 351	Geshkenbein	(ITEP)
ANTONELLI	88	PL B212 133	+Baldini+	(DM2 Collab.)
DIEKMAN	88	PRPL 159 101		(BONN)
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
DONNACHIE	87B	ZPHY C34 257	+Clegg	(MCHS, LANC)
ATKINSON	86B	ZPHY C30 531	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	85B	ZPHY C26 499	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ERKAL	85	ZPHY C29 485	+Olsson	(WISC)
ABE	84B	PRL 53 751	+Bacon, Ballam+	(SLAC Hybrid Facility Photon Collab.)
ATKINSON	82	PL 108B 55	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BUON	82	PL 118B 221	+Bisello, Bizot, Cordier, Delcourt+	(LALO, MONP)
CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
CORDIER	82	PL 109B 129	+Bisello, Bizot, Buon, Delcourt	(LALO)
DELCOURT	82	PL 113B 93	+Bisello, Bizot, Buon, Cordier, Mane	(LALO)
ASTON	81E	NP B189 15		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT	81B	Bonn Conf. 205		(ORSAY)
Also	82	PL 109B 129	Cordier, Bisello, Bizot, Buon, Delcourt	(LALO)
DIBIANCA	81	PR D23 595	+Fickinger, Malko, Dado, Engler+	(CASE, CMU)
ASTON	80	PL 92B 215		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BACCI	80	PL 95B 139	+DeZorzi, Penso, Baldini-Celio+	(ROMA, FRAS)
BIZOT	80	Madison Conf. 546	+Bisello, Buon, Cordier, Delcourt+	(LALO, MONP)
KILLIAN	80	PR D21 3005	+Treadwell, Ahrens, Berkelman, Cassel+	(CORN)
ATIYA	79B	PRL 43 1691	+Holmes, Knapp, Lee, Seto+	(COLU, ILL, FNAL)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
LANG	79	PR D19 956	+Mas-Parareda	(GRAZ)
MARTIN	78C	ANP 114 1	+Pennington	(CERN)
COSTA...	77B	PL 71B 345	Costa De Beauregard, Pire, Truong	(EPOL)
FROGGATT	77	NP B129 89	+Petersen	(GLAS, NORD)
ALEXANDER	75	PL 57B 487	+Benary, Gandsman, Lissauer+	(TELA)
BALLAM	74	NP B76 375	+Chadwick, Bingham, Fretter+	(SLAC, LBL, MPIM)
CONVERSI	74	PL 52B 493	+Paoluzi, Ceradini, Grilli+	(ROMA, FRAS)
SCHACHT	74	NP B81 205	+Derado, Fries, Park, Yount	(MPIM)
DAVIER	73	NP B58 31	+Derado, Fries, Liu, Mozley, Odian, Park+	(SLAC)
EISENBERG	73	PL 43B 149	+Karshon, Mikenberg, Pitluck+	(REHO)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
BINGHAM	72B	PL 41B 635	+Rabin, Rosenfeld, Smadja+	(LBL, UCB, SLAC) IGJP

OTHER RELATED PAPERS

BARNES	97	PR D55 4157	T. Barnes+	(ORNL, RAL, MCHS)
CLOSE	97C	PR D56 1584	F.E. Close+	(RAL, MCHS)
URHEIM	97	NPBPS 55C 359	J. Urheim	(CLEO Collab.)
ACHASOV	96B	PAN 59 1262 Translated from YAF 59 1319.	+Shestakov	(NOVM)
AMSLER	93B	PL B311 362	+Armstrong, v.Dombrowski+	(Crystal Barrel Collab.)
LANDSBERG	92	SJNP 55 1051 Translated from YAF 55 1896.		(SERP)
ASTON	91B	NPBPS 21 105	+Awaji, Bienz+	(LASS Collab.)
DONNACHIE	91	ZPHY C51 689	+Clegg	(MCHS, LANC)
ACHASOV	88C	PL B209 373	+Kozhevnikov	(NOVM)
BRAU	88	PR D37 2379	+Franek+	(SLAC Hybrid Facility Photon Collab.) JP
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ERKAL	86	ZPHY C31 615	+Olsson	(WISC)
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
ATKINSON	84C	NP B243 1	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
ATKINSON	83B	PL 127B 132	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	83C	NP B229 269	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
AUGUSTIN	83	LAL 83-21	+Ayach, Bisello, Baldini+	(LALO, PADO, FRAS)
SHAMBROOM	82	PR D26 1	+Wilson, Anderson, Francis+	(HARV, EFI, ILL, OXF)
ASTON	80C	PL 92B 211		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER	80C	ZPHY C4 169	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)
KILLIAN	80	PR D21 3005	+Treadwell, Ahrens, Berkelman, Cassel+	(CORN)
COSME	76	PL 63B 352	+Courau, Dudelzak, Grelaud, Jean-Marie+	(ORSAY)
FRENKIEL	72	NP B47 61	+Ghesquiere, Lillestol, Chung+	(CDEF, CERN)
ALVENSLEB...	71	PRL 26 273	Alvensleben, Becker, Bertram, Chen+	(DESY, MIT) G
BRAUN	71	NP B30 213	+Fridman, Gerber, Givernaud+	(STRB) G
BULOS	71	PRL 26 149	+Busza, Kehoe, Beniston+	(SLAC, UMD, IBM, LBL) G
LAYSSAC	71	NC 6A 134	+Renard	(MONP)

$f_J(1710)$

$I^G(J^{PC}) = 0^+(\text{even}^{++})$

THE $f_J(1710)$

Written March 1998 by M. Doser (CERN).

The $f_J(1710)$ is seen in the radiative decay $J/\psi(1S) \to \gamma f_J(1710)$; therefore $C = +1$. It decays into 2η and $K_S^0 K_S^0$, which implies $I^G J^{PC} = 0^+(\text{even})^{++}$. The spin of the $f_J(1710)$ is controversial. Combined amplitude analyses of the K^+K^-, $K_S K_S$ and $\pi^+\pi^-$ systems produced in $J/\psi(1S)$ radiative decay (in recent and some earlier unpublished analyses by the Mark III Collaboration) find a large spin-0 component, as well as reproducing known parameters of the $f_2(1270)$ and $f_2'(1525)$. A recent reanalysis (BUGG 95) of the 4π channel from MARK III, allowing both $\rho\rho$ and two $\pi\pi$ S waves, finds two states, a 0^{++} at ~ 1750 MeV and a 2^{++} at ~ 1620 MeV. Earlier analyses of the $\rho\rho$ final state (BISELLO 89B, BALTRUSAITIS 86B) found only pseudoscalar activity in the $f_J(1710)$ region, but considered only the process $J/\psi(1S) \to \gamma\rho\rho$. In contrast, a spin 2 was found for the $f_J(1710)$ in earlier analyses of the $\eta\eta$ (BLOOM 83) or K^+K^- (BALTRUSAITIS 87) systems based on less statistics. More recently, an analysis of the K^+K^- channel finds indications for a lower mass tensor as well as a higher mass scalar state (BAI 96C).

In pp central production at 300 GeV/c in both K^+K^- and $K_S^0 K_S^0$, $f_J(1710)$ is definitely spin 2 (ARMSTRONG 89D). More recent analyses with greater statistics (E690 Collaboration, unpublished) are, however, not able to differentiate between spin 0 and 2. Generally, analyses preferring spin 2 concentrate on angular distributions in the $f_J(1710)$ region, and do not include possible interferences or distortion due to the nearby $f_2'(1525)$.

The $f_J(1710)$ is also observed in $K\overline{K}$ (FALVARD 88) in $J/\psi(1S) \to \omega K\overline{K}$ and $J/\psi(1S) \to \phi K\overline{K}$, but with no spin-parity analysis. ARMSTRONG 93C also sees a broad peak at 1747 MeV in $p\overline{p}$ annihilation into $\eta\eta$, which may be the $f_J(1710)$. This resonance is not observed in the hypercharge-exchange reactions $K^-p \to K_S^0 K_S^0 \Lambda$ (ASTON 88D) and $K^-p \to K_S^0 K_S^0 Y^*$ (BOLONKIN 86).

A partial-wave analysis of the $K_S^0 K_S^0$ system in $\pi^- p \to K_S^0 K_S^0 n$ (BOLONKIN 88) finds a D_0-wave behavior ($J^{PC} = 2^{++}$) near 1700 MeV, but the width (~ 30 MeV) is much smaller than those observed in $J/\psi(1S)$ decays and in hadroproduction. The 0^{++} wave shows, however a broad enhancement around 1720 MeV.

$f_J(1710)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1712± 5 OUR AVERAGE	Error includes scale factor of 1.1.			
1713±10	[1] ARMSTRONG	89D	OMEG	300 $pp \to ppK^+K^-$
1706±10	[1] ARMSTRONG	89D	OMEG	300 $pp \to ppK_S^0K_S^0$
1707±10	[2] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$, $K_S^0K_S^0$
1698±15	[2] AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1720±10±10	[3] BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
1742±15	[2] WILLIAMS	84	MPSF	200 $\pi^- N \to 2K_S^0 X$
1670±50	BLOOM	83	CBAL	$J/\psi \to \gamma 2\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1704^{+16}_{-23}	[4] DUNWOODIE	97		$J/\psi \to K\overline{K}$, $\pi\pi$
1690±11	[5] ABREU	96C	DLPH	$\gamma\gamma \to K^+K^-$ E_{cm}^{ee}= 91.2 GeV
$1696\pm 5^{+9}_{-34}$	[3] BAI	96C	BES	$J/\psi \to \gamma K^+K^-$
$1781\pm 8^{+10}_{-31}$	[6] BAI	96C	BES	$J/\psi \to \gamma K^+K^-$
1768±14	BALOSHIN	95	SPEC	40 $\pi^- C \to K_S^0K_S^0X$
1750±15	[7] BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1620±16	[3] BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1748±10	[2] ARMSTRONG	93C	E760	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
~ 1750	BREAKSTONE	93	SFM	$pp \to pp\pi^+\pi^-\pi^+\pi^-$
1744±15	[8] ALDE	92D	GAM2	38 $\pi^- p \to \eta\eta N^*$
1700±15	[3] BOLONKIN	88	SPEC	40 $\pi^- p \to K_S^0K_S^0n$
1720±60	[6] BOLONKIN	88	SPEC	40 $\pi^- p \to K_S^0K_S^0n$
1638±10	[9] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$, $K_S^0K_S^0$
1690± 4	[10] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$, $K_S^0K_S^0$
1730^{+2}_{-10}	[11] LONGACRE	86	RVUE	22 $\pi^- p \to n2K_S^0$
1650±50	BURKE	82	MRK2	$J/\psi \to \gamma 2\rho$
1640±50	[12,13] EDWARDS	82D	CBAL	$J/\psi \to \gamma 2\eta$
1730±10±20	[14] ETKIN	82C	MPS	23 $\pi^- p \to n2K_S^0$

[1] $J^P = 2^+$, (0^+ excluded).
[2] No J^{PC} determination.
[3] $J^P = 2^+$.

[4] $J^P = 0^+$, reanalysis of MARK III data.
[5] No J^{PC} determination, width not determined.
[6] $J^P = 0^+$.
[7] From a fit to the 0^+ partial wave.
[8] ALDE 92D combines all the GAMS-2000 data.
[9] From an analysis ignoring interference with $f'_2(1525)$.
[10] From an analysis including interference with $f'_2(1525)$.
[11] Uses MRK3 data. From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2. Fit with constrained inelasticity.
[12] $J^P = 2^+$ preferred.
[13] From fit neglecting nearby $f'_2(1525)$. Replaced by BLOOM 83.
[14] Superseded by LONGACRE 86.

$f_J(1710)$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
133 ± 14 OUR AVERAGE		Error includes scale factor of 1.2.		
181 ± 30		[15] ARMSTRONG 89D	OMEG	300 $pp \to ppK^+K^-$
104 ± 30		[15] ARMSTRONG 89D	OMEG	300 $pp \to ppK^0_SK^0_S$
166.4 ± 33.2		[16] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+K^-$, $K^0_SK^0_S$
136 ± 28		[16] AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
130 ± 20		[17] BALTRUSAIT...87	MRK3	$J/\psi \to \gamma K^+K^-$
57 ± 38		[2] WILLIAMS 84	MPSF	200 $\pi^- N \to 2K^0_S X$
160 ± 80		BLOOM 83	CBAL	$J/\psi \to \gamma 2\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$124 {+52 \atop -44}$		[18] DUNWOODIE 97		$J/\psi \to K\overline{K}$, $\pi\pi$
$103 \pm 18 {+30 \atop -11}$		[17] BAI 96C	BES	$J/\psi \to \gamma K^+K^-$
$85 \pm 24 {+22 \atop -19}$		[19] BAI 96C	BES	$J/\psi \to \gamma K^+K^-$
56 ± 19		BALOSHIN 95	SPEC	40 $\pi^- C \to K^0_SK^0_S X$
160 ± 40		[20] BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
$160 {+60 \atop -20}$		[17] BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
264 ± 25		[16] ARMSTRONG 93C	E760	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
200 to 300		BREAKSTONE 93	SFM	$pp \to pp\pi^+\pi^-\pi^+\pi^-$
< 80	90	[21] ALDE 92D	GAM2	38 $\pi^- p \to \eta\eta N^*$
30 ± 20		[17] BOLONKIN 88	SPEC	40 $\pi^- p \to K^0_SK^0_S n$
350 ± 150		[19] BOLONKIN 88	SPEC	40 $\pi^- p \to K^0_SK^0_S n$
148 ± 17		[22] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$, $K^0_SK^0_S$
184 ± 6		[23] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$, $K^0_SK^0_S$
$122 {+74 \atop -15}$		[24] LONGACRE 86	RVUE	22 $\pi^- p \to n2K^0_S$
200 ± 100		BURKE 82	MRK2	$J/\psi \to \gamma 2\rho$
$220 {+100 \atop -70}$		[25,26] EDWARDS 82D	CBAL	$J/\psi \to \gamma 2\eta$
$200.0 {+156.0 \atop -9.0}$		[27] ETKIN 82B	MPS	23 $\pi^- p \to n2K^0_S$

[15] $J^P = 2^+$, (0^+ excluded).
[16] No J^{PC} determination.
[17] $J^P = 2^+$.
[18] $J^P = 0^+$, reanalysis of MARK III data.
[19] $J^P = 0^+$.
[20] From a fit to the 0^+ partial wave.
[21] ALDE 92D combines all the GAMS-2000 data.
[22] From an analysis ignoring interference with $f'_2(1525)$.
[23] From an analysis including interference with $f'_2(1525)$.
[24] Uses MRK3 data. From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2. Fit with constrained inelasticity.
[25] $J^P = 2^+$ preferred.
[26] From fit neglecting nearby $f'_2(1525)$. Replaced by BLOOM 83.
[27] From an amplitude analysis of the $K^0_SK^0_S$ system, superseded by LONGACRE 86.

$f_J(1710)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\eta\eta$	seen
Γ_3	$\pi\pi$	seen
Γ_4	pp	
Γ_5	$\gamma\gamma$	

$f_J(1710)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.11	95	[28] BEHREND 89C	CELL	$\gamma\gamma \to K^0_SK^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.48	95	ALBRECHT 90G	ARG	$\gamma\gamma \to K^+K^-$
<0.28	95	[28] ALTHOFF 85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[28] Assuming helicity 2.

$f_J(1710)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.38 {+0.09 \atop -0.19}$	[29,30] LONGACRE 86	MPS	22 $\pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$0.18 {+0.03 \atop -0.13}$	[29,30] LONGACRE 86	RVUE

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$0.039 {+0.002 \atop -0.024}$	[29,30] LONGACRE 86	RVUE

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ Γ_3/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.39±0.14	ARMSTRONG 91	OMEG	300 $pp \to pp\pi\pi$, $ppK\overline{K}$

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	90	[31] PROKOSHKIN 91	GA24	300 $\pi^- p \to \pi^- p\eta\eta$

[29] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[30] Fit with constrained inelasticity.
[31] Combining results of GAM4 with those of ARMSTRONG 89D.

$f_J(1710)$ REFERENCES

DUNWOODIE	97	Hadron 97 Conf.	W. Dunwoodie	(SLAC)
ABREU	96C	PL B379 309	+Adam, Adye+	(DELPHI Collab.)
BAI	96C	PRL 77 3959	J.Z. Bai+	(BES Collab.)
BALOSHIN	95	PAN 58 46	+Bolonkin, Vladimirskii+	(ITEP)
		Translated from YAF 58 50.		
BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
ARMSTRONG	93C	PL B307 394	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
BREAKSTONE	93	ZPHY C58 251	+Campanini+	(IOWA, CERN, DORT, HEIDH, WARS)
ALDE	92D	PL B284 457	+Binon, Bricman+	(GAM2 Collab.)
Also	91	SJNP 54 451	Alde, Binon, Bricman+	(GAM2 Collab.)
		Translated from YAF 54 745.		
ARMSTRONG	91	ZPHY C51 351	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
PROKOSHKIN	91	SPD 36 155		(GAM2, GAM4 Collab.)
		Translated from DANS 316 900.		
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
BEHREND	89C	ZPHY C43 91	+Criegee, Dainton+	(CELLO Collab.)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
WILLIAMS	84	PR D30 877	+Diamond+	(VAND, NDAM, TUFTS, ARIZ, FNAL+)
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
BURKE	82	PRL 49 632	+Trilling, Abrams, Alam, Blocker+	(LBL, SLAC)
EDWARDS	82D	PRL 48 458	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)

OTHER RELATED PAPERS

ANISOVICH	97	PL B395 123	+Sarantsev	(PNPI)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ARMSTRONG	86B	PL 167B 133	+Bloodworth, Carney+	(ATHU, BARI, BIRM, CERN)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
BARNETT	83B	PL 120B 455	+Blockus, Burka, Chien, Christian+	(JHU)
ALTHOFF	82	ZPHY C16 13	+Boerner, Burkhardt+	(TASSO Collab.)
BARNES	82	PL B116 365	+Close	(RHEL)
BARNES	82B	NP B198 360	+Close, Monaghan	(RHEL, OXFTP)
TANIMOTO	82	PL 116B 198		(BIEL)

$\eta(1760)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by DM2 in the $\rho\rho$ system (BISELLO 89B). Structure in this region has been reported before in the same system (BALTRUSAITIS 86B) and in the $\omega\omega$ system (BALTRUSAITIS 85C, BISELLO 87). Needs confirmation.

$\eta(1760)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1760±11	320	[1] BISELLO	89B	DM2	$J/\psi \rightarrow 4\pi\gamma$

[1] Estimated by us from various fits.

$\eta(1760)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
60±16	320	[2] BISELLO	89B	DM2	$J/\psi \rightarrow 4\pi\gamma$

[2] Estimated by us from various fits.

$\eta(1760)$ REFERENCES

BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
BISELLO	87	PL B192 239	+Ajaltouni, Baldini+	(PADO, CLER, FRAS, LALO)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BALTRUSAIT...	85C	PRL 55 1723	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)

$X(1775)$

$I^G(J^{PC}) = 1^-(?^{-+})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$X(1775)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1776±13 OUR AVERAGE				
1763±20	CONDO	91	SHF	$\gamma p \rightarrow (p\pi^+)(\pi^+\pi^-\pi^-)$
1787±18	CONDO	91	SHF	$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

$X(1775)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
155±40 OUR AVERAGE				
192±60	CONDO	91	SHF	$\gamma p \rightarrow (p\pi^+)(\pi^+\pi^-\pi^-)$
118±60	CONDO	91	SHF	$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

$X(1775)$ DECAY MODES

	Mode
Γ_1	$\rho\pi$
Γ_2	$f_2(1270)\pi$

$X(1775)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(f_2(1270)\pi)$ **Γ_1/Γ_2**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.43±0.26 OUR AVERAGE				
1.3 ±0.3	CONDO	91	SHF	$\gamma p \rightarrow (p\pi^+)(\pi^+\pi^-\pi^-)$
1.8 ±0.5	CONDO	91	SHF	$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

$X(1775)$ REFERENCES

CONDO	91	PR D43 2787	+Handler+	(SLAC Hybrid Collab.)

$\pi(1800)$

$I^G(J^{PC}) = 1^-(0^{-+})$

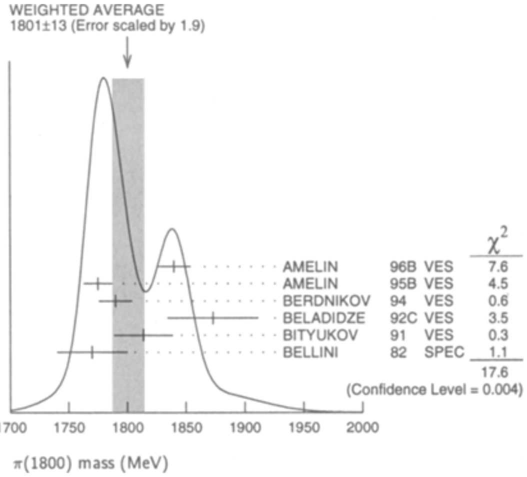
See also minireview under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\pi(1800)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1801±13 OUR AVERAGE Error includes scale factor of 1.9. See the ideogram below.						
1840±10±10	1200	AMELIN	96B	VES	−	37 $\pi^- A \rightarrow \eta\eta\pi^- A$
1775± 7±10		[1] AMELIN	95B	VES	−	36 $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$
1790±14		[2] BERDNIKOV	94	VES	−	37 $\pi^- A \rightarrow K^+K^-\pi^- A$
1873±33±20		BELADIDZE	92C	VES	−	36 $\pi^- \mathrm{Be} \rightarrow \pi^-\eta'\eta\mathrm{Be}$
1814±10±23	426±57	BITYUKOV	91	VES	−	36 $\pi^- \mathrm{C} \rightarrow \pi^-\eta\eta\mathrm{C}$
1770±30	1100	BELLINI	82	SPEC	−	40 $\pi^- \mathrm{A} \rightarrow 3\pi\mathrm{A}$

[1] From a fit to $J^{PC} = 0^{-+}$ $f_0(980)\pi$, $f_0(1370)\pi$ waves.

[2] From a fit to $J^{PC} = 0^{-+}$ $K_0^*(1430)K^-$ and $f_0(980)\pi^-$ waves.



$\pi(1800)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
210±15 OUR AVERAGE						
210±30±30	1200	AMELIN	96B	VES	−	37 $\pi^- A \rightarrow \eta\eta\pi^- A$
190±15±15		[3] AMELIN	95B	VES	−	36 $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$
210±70		[4] BERDNIKOV	94	VES	−	37 $\pi^- A \rightarrow K^+K^-\pi^- A$.
225±35±20		BELADIDZE	92C	VES	−	36 $\pi^- \mathrm{Be} \rightarrow \pi^-\eta'\eta\mathrm{Be}$
205±18±32	426±57	BITYUKOV	91	VES	−	36 $\pi^- \mathrm{C} \rightarrow \pi^-\eta\eta\mathrm{C}$
310±50	1100	BELLINI	82	SPEC	−	40 $\pi^- \mathrm{A} \rightarrow 3\pi\mathrm{A}$

[3] From a fit to $J^{PC} = 0^{-+}$ $f_0(980)\pi$, $f_0(1370)\pi$ waves.

[4] From a fit to $J^{PC} = 0^{-+}$ $K_0^*(1430)K^-$ and $f_0(980)\pi^-$ waves.

$\pi(1800)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^-$	seen
Γ_2	$f_0(980)\pi^-$	seen
Γ_3	$f_0(1370)\pi^-$	seen
Γ_4	$\rho\pi^-$	not seen
Γ_5	$\eta\eta\pi^-$	seen
Γ_6	$a_0(980)\eta$	seen
Γ_7	$f_0(1500)\pi^-$	seen
Γ_8	$\eta\eta'(958)\pi^-$	seen
Γ_9	$K_0^*(1430)K^-$	seen
Γ_{10}	$K^*(892)K^-$	not seen

$\pi(1800)$ BRANCHING RATIOS

$\Gamma(f_0(980)\pi^-)/\Gamma(f_0(1370)\pi^-)$ Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
1.7±1.3	AMELIN 95B	VES	−	36 $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$

$\Gamma(f_0(1370)\pi^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	BELLINI 82	SPEC	−	40 $\pi^- A \rightarrow 3\pi A$

$\Gamma(\eta\eta\pi^-)/\Gamma(\pi^+\pi^-\pi^-)$ Γ_5/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.5 ±0.1	1200	AMELIN 96B	VES	−	37 $\pi^- A \rightarrow \eta\eta\pi^- A$

$\Gamma(f_0(1500)\pi^-)/\Gamma(a_0(980)\eta)$ Γ_7/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.08 ±0.03	1200	[5] AMELIN 96B	VES	−	37 $\pi^- A \rightarrow \eta\eta\pi^- A$

[5] Assuming that $f_0(1500)$ decays only to $\eta\eta$ and $a_0(980)$ decays only to $\eta\pi$.

$\Gamma(\eta\eta'(958)\pi^-)/\Gamma(\eta\eta\pi^-)$ Γ_8/Γ_5

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.29±0.06 OUR AVERAGE					
0.29±0.07		BELADIDZE 92C	VES	−	36 $\pi^- \text{Be} \rightarrow \pi^-\eta'\eta\text{Be}$
0.3 ±0.1	426±57	BITYUKOV 91	VES	−	36 $\pi^- \text{C} \rightarrow \pi^-\eta\eta\text{C}$

$\Gamma(K_0^*(1430)K^-)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	BERDNIKOV 94	VES	−	37 $\pi^- A \rightarrow K^+K^-\pi^- A$

$\Gamma(K^*(892)K^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	BERDNIKOV 94	VES	−	37 $\pi^- A \rightarrow K^+K^-\pi^- A$

$\Gamma(\rho\pi^-)/\Gamma(f_0(980)\pi^-)$ Γ_4/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.14	90	AMELIN 95B	VES	−	36 $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$

$\Gamma(\rho\pi^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
not seen	BELLINI 82	SPEC	−	40 $\pi^- A \rightarrow 3\pi A$

$\pi(1800)$ REFERENCES

AMELIN 96B PAN 59 976 +Berdnikov, Bityukov+ (SERP, TBIL) IGJPC
Translated from YAF 59 1021.
AMELIN 95B PL B356 595 +Berdnikov, Bityukov+ (SERP, TBIL)
BERDNIKOV 94 PL B337 219 +Bityukov+ (SERP, TBIL)
BELADIDZE 92C SJNP 55 1535 +Bityukov, Borisov (SERP, TBIL)
Translated from YAF 55 2748.
BITYUKOV 91 PL B268 137 +Borisov+ (SERP, TBIL)
BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)

OTHER RELATED PAPERS

BORISOV 92 SJNP 55 1441 +Gershtein, Zaitsev (SERP)
Translated from YAF 55 2583.

$f_2(1810)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$f_2(1810)$ MASS

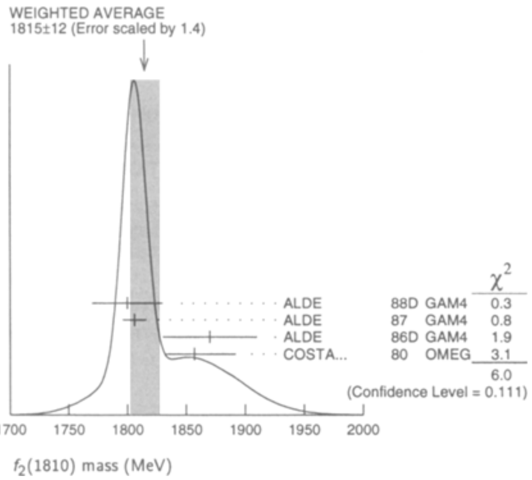
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1815±12 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
1800±30	40	ALDE 88D	GAM4	300 $\pi^- p \rightarrow \pi^- p 4\pi^0$
1806±10	1600	ALDE 87	GAM4	100 $\pi^- p \rightarrow 4\pi^0 n$
1870±40		[1] ALDE 86D	GAM4	100 $\pi^- p \rightarrow \eta\eta n$
1857^{+35}_{-24}		[2] COSTA... 80	OMEG	10 $\pi^- p \rightarrow K^+K^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1858^{+18}_{-71}		[3] LONGACRE 86	RVUE	Compilation
1799±15		[4] CASON 82	STRC	8 $\pi^+ p \rightarrow \Delta^{++}\pi^0\pi^0$

[1] Seen in only one solution.

[2] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

[3] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[4] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$. The resonance in the $2\pi^0$ final state is not confirmed by PROKOSHKIN 97.



$f_2(1810)$ WIDTH

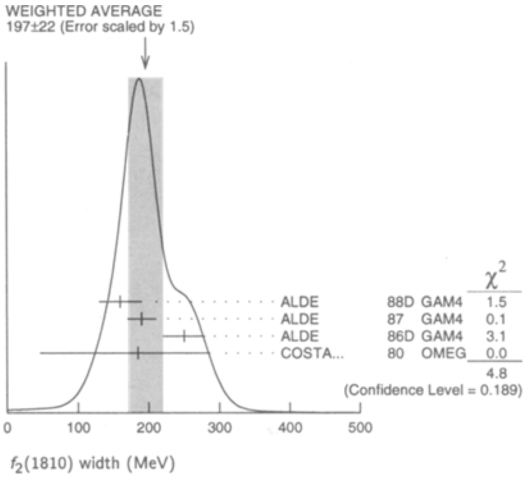
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
197± 22 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
160± 30	40	ALDE 88D	GAM4	300 $\pi^- p \rightarrow \pi^- p 4\pi^0$
190± 20	1600	ALDE 87	GAM4	100 $\pi^- p \rightarrow 4\pi^0 n$
250± 30		[5] ALDE 86D	GAM4	100 $\pi^- p \rightarrow \eta\eta n$
185^{+102}_{-139}		[6] COSTA... 80	OMEG	10 $\pi^- p \rightarrow K^+K^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
388^{+15}_{-21}		[7] LONGACRE 86	RVUE	Compilation
280^{+42}_{-35}		[8] CASON 82	STRC	8 $\pi^+ p \rightarrow \Delta^{++}\pi^0\pi^0$

[5] Seen in only one solution.

[6] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

[7] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[8] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$. The resonance in the $2\pi^0$ final state is not confirmed by PROKOSHKIN 97.



$f_2(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	
Γ_2	$\eta\eta$	
Γ_3	$4\pi^0$	seen
Γ_4	K^+K^-	

$f_2(1810)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	PROKOSHKIN	97	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
$0.21^{+0.02}_{-0.03}$	[9] LONGACRE	86	RVUE	Compilation
0.44 ± 0.03	[10] CASON	82	STRC	$8\ \pi^+ p \to \Delta^{++}\pi^0\pi^0$

[9] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[10] Included in LONGACRE 86 global analysis.

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ **Γ_2/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.008^{+0.028}_{-0.003}$	[9] LONGACRE	86	RVUE	Compilation

$\Gamma(\pi\pi)/\Gamma(4\pi^0)$ **Γ_1/Γ_3**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.75	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ **Γ_3/Γ_2**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8 ± 0.3	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ **Γ_4/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.003^{+0.019}_{-0.002}$	[9] LONGACRE	86	RVUE	Compilation
seen	COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$

$f_2(1810)$ REFERENCES

PROKOSHKIN 97 SPD 42 117 +Kondashov, Sadovsky+ (SERP)
Translated from DANS 353 323.
ALDE 88D SJNP 47 810 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
Translated from YAF 47 1273.
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
CASON 82 PRL 48 1316 +Biswas, Baumbaugh, Bishop+ (NDAM, ANL)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)

OTHER RELATED PAPERS

AKER 91 PL B260 249 +Amsler, Peters+ (Crystal Barrel Collab.)
CASON 83 PR D28 1586 +Cannata, Baumbaugh, Bishop+ (NDAM, ANL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)

$\phi_3(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\phi_3(1850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1854± 7 OUR AVERAGE					
1855 ± 10		ASTON	88E	LASS	$11\ K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
1870^{+30}_{-20}	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
1850 ± 10	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
87^{+28}_{-23} OUR AVERAGE Error includes scale factor of 1.2.					
64 ± 31		ASTON	88E	LASS	$11\ K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
160^{+90}_{-50}	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
80^{+40}_{-30}	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$K\overline{K}^*(892)+$ c.c.	seen

$\phi_3(1850)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K})$ **Γ_2/Γ_1**

VALUE	DOCUMENT ID		TECN	COMMENT
$0.55^{+0.85}_{-0.45}$	ASTON	88E	LASS	$11\ K^- p \to K^- K^+ \Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.8\ \pm0.4$	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\pi\Lambda$

$\phi_3(1850)$ REFERENCES

ASTON 88E PL B208 324 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS) IGJPC
ARMSTRONG 82 PL 110B 77 +Baubillier+ (BARI, BIRM, CERN, MILA, CURIN+) JP
ALHARRAN 81B PL 101B 357 +Amirzadeh+ (BIRM, CERN, GLAS, MICH, CURIN)

OTHER RELATED PAPERS

CORDIER 82B PL 110B 335 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 80B PL 92B 219 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\eta_2(1870)$

$I^G(J^{PC}) = 0^+(2^{-+})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$\eta_2(1870)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1854±20 OUR AVERAGE						
1840 ± 25		BARBERIS	97B	OMEG		$450\ pp \to pp2(\pi^+\pi^-)$
$1875\pm20\pm35$		ADOMEIT	96	CBAR	0	$1.94\ \overline{p}p \to \eta 3\pi^0$
$1881\pm32\pm40$	26	KARCH	92	CBAL		$e^+e^- \to e^+e^-\eta\pi^0\pi^0$

$\eta_2(1870)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
202±30 OUR AVERAGE						
200 ± 40		BARBERIS	97B	OMEG		$450\ pp \to pp2(\pi^+\pi^-)$
$200\pm25\pm45$		ADOMEIT	96	CBAR	0	$1.94\ \overline{p}p \to \eta 3\pi^0$
$221\pm92\pm44$	26	KARCH	92	CBAL		$e^+e^- \to e^+e^-\eta\pi^0\pi^0$

$\eta_2(1870)$ DECAY MODES

	Mode
Γ_1	$\eta\pi\pi$
Γ_2	$a_2(1320)\pi$
Γ_3	$f_2(1270)\eta$

η_2(1870) BRANCHING RATIOS

$\Gamma(a_2(1320)\pi)/\Gamma(f_2(1270)\eta)$ **Γ_2/Γ_3**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
4.1±2.3	ADOMEIT	96	CBAR	0	1.94 $\bar{p}p \to \eta 3\pi^0$

η_2(1870) REFERENCES

BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)
ADOMEIT	96	ZPHY C71 227	+Amsler, Armstrong+	(Crystal Barrel Collab.)
KARCH	92	ZPHY C54 33	+Antreasyan, Bartels+	(Crystal Ball Collab.)

——— OTHER RELATED PAPERS ———

KARCH	90	PL B249 353	+Antreasyan, Bartels+	(Crystal Ball Collab.)

X(1910)

$I^G(J^{PC}) = 0^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

We list here two different peaks with close masses and widths seen in the mass distributions of $\omega\omega$ and $\eta\eta'$ final states. ALDE 91B argues that they are of different nature.

X(1910) MASS

VALUE (MeV)	*DOCUMENT ID*
1810 to 1920 OUR ESTIMATE	

X(1910) $\omega\omega$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1921± 8 OUR AVERAGE				
1920±10	[1] BELADIDZE	92B	VES	36 $\pi^- p \to \omega\omega n$
1924±14	[1] ALDE	90	GAM2	38 $\pi^- p \to \omega\omega n$

[1] $J^{PC} = 2^{++}$.

X(1910) $\eta\eta'$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1911±10	ALDE	91B	GAM2	38 $\pi^- p \to \eta\eta' n$

X(1910) WIDTH

VALUE (MeV)	*DOCUMENT ID*
90 to 250 OUR ESTIMATE	

X(1910) $\omega\omega$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
90±19 OUR AVERAGE				
90±20	[2] BELADIDZE	92B	VES	36 $\pi^- p \to \omega\omega n$
91±50	[2] ALDE	90	GAM2	38 $\pi^- p \to \omega\omega n$

[2] $J^{PC} = 2^{++}$.

X(1910) $\eta\eta'$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
90±35	ALDE	91B	GAM2	38 $\pi^- p \to \eta\eta' n$

X(1910) DECAY MODES

	Mode
Γ_1	$\pi^0\pi^0$
Γ_2	$K^0_S K^0_S$
Γ_3	$\eta\eta$
Γ_4	$\omega\omega$
Γ_5	$\eta\eta'$
Γ_6	$\eta'\eta'$

X(1910) BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ **Γ_4/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ALDE	89B	GAM2	38 $\pi^- p \to \omega\omega n$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta')$ **Γ_1/Γ_5**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.1	ALDE	89	GAM2	38$\pi^- p \to \eta\eta' n$

$\Gamma(\eta\eta)/\Gamma(\eta\eta')$ **Γ_3/Γ_5**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	ALDE	91B	GAM2	38 $\pi^- p \to \eta\eta' n$

$\Gamma(K^0_S K^0_S)/\Gamma(\eta\eta')$ **Γ_2/Γ_5**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.066	90	BALOSHIN	86	SPEC	40$\pi p \to K^0_S K^0_S n$

$\Gamma(\eta'\eta')/\Gamma_{\text{total}}$ **Γ_6/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	BELADIDZE	92D	VES	37 $\pi^- p \to \eta'\eta' n$

X(1910) REFERENCES

BELADIDZE	92B	ZPHY C54 367	+Bityukov, Borisov+	(VES Collab.)
BELADIDZE	92D	ZPHY C57 13	+Berdnikov+	(VES Collab.)
ALDE	91B	SJNP 54 455	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
		Translated from YAF 54 751.		
Also	92	PL B276 375	Alde, Binon+	(BELG, SERP, KEK, LANL, LAPP)
ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	89	PL B216 447	+Binon, Bricman, Donskov+	(SERP, BELG, LANL, LAPP)
Also	88E	SJNP 48 1035	Alde, Binon, Bricman+	(BELG, SERP, LANL, LAPP)
		Translated from YAF 48 1724.		
ALDE	89B	PL B216 451	+Binon, Bricman+	(SERP, BELG, LANL, LAPP, TBIL)
BALOSHIN	86	SJNP 43 959	+Barkov, Bolonkin, Vladimirskii, Grigoriev+	(ITEP)
		Translated from YAF 43 1487.		

——— OTHER RELATED PAPERS ———

LEE	94	PL B323 227	+Chung, Kirk+	(BNL, IND, KYUN, MASD, RICE)

f_2(1950)

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

f_2(1950) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1960±30	[1] BARBERIS	97B	OMEG		450 $pp \to pp2(\pi^+\pi^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1918±12	ANTINORI	95	OMEG		300,450 $pp \to pp2(\pi^+\pi^-)$
~ 1996	HASAN	94	RVUE		$\bar{p}p \to \pi\pi$
~ 1990	[2] OAKDEN	94	RVUE		0.36–1.55 $\bar{p}p \to \pi^+\pi^-$
1950±15	[3] ASTON	91	LASS	0	11 $K^- p \to \Lambda K\bar{K}\pi\pi$

[1] Possibly two states.

[2] From solution B of amplitude analysis of data on $\bar{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[3] Cannot determine spin to be 2.

f_2(1950) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
460±40	[4] BARBERIS	97B	OMEG		450 $pp \to pp2(\pi^+\pi^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
390±60	ANTINORI	95	OMEG		300,450 $pp \to pp2(\pi^+\pi^-)$
~ 134	HASAN	94	RVUE		$\bar{p}p \to \pi\pi$
~ 100	[5] OAKDEN	94	RVUE		0.36–1.55 $\bar{p}p \to \pi^+\pi^-$
250±50	[6] ASTON	91	LASS	0	11 $K^- p \to \Lambda K\bar{K}\pi\pi$

[4] Possibly two states.

[5] From solution B of amplitude analysis of data on $\bar{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[6] Cannot determine spin to be 2.

f_2(1950) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\overline{K}^*(892)$	seen
Γ_2	$\pi^+\pi^-$	seen
Γ_3	$\pi^+\pi^-\pi^+\pi^-$	possibly seen
Γ_4	$a_2(1320)\pi$	
Γ_5	$f_2(1270)\pi\pi$	

$f_2(1950)$ BRANCHING RATIOS

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ASTON	91	LASS	0	11 $K^- p \to \Lambda K \overline{K} \pi\pi$

$\Gamma(a_2(1320)\pi)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	BARBERIS	97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$

$f_2(1950)$ REFERENCES

BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)
KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
ANTINORI	95	PL B353 589	+Barberis, Bayes+	(ATHU, BARI, BIRM, CERN, JINR) JP
HASAN	94	PL B334 215	+Bugg	(LOQM)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)
ASTON	91	NP B21 5 (suppl)	+Awaji+	(LASS Collab.)

OTHER RELATED PAPERS

ALBRECHT	88N	PL B212 528	+	(ARGUS Collab.)
ALBRECHT	87Q	PL B198 255	+Binder+	(ARGUS Collab.)
ARMSTRONG	87C	ZPHY C34 33	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)

$X(2000)$

$I^G(J^{PC}) = 1^-(?^{?+})$

OMITTED FROM SUMMARY TABLE

BALTAY 77 favors $J^P = 3^+$. Needs confirmation.

$X(2000)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1964±35		[1] ARMSTRONG	93D	E760		$\overline{p}p \to 3\pi^0 \to 6\gamma$
~ 2100		[1] ANTIPOV	77	CIBS	−	25 $\pi^- p \to p\pi^- \rho_3$
2214±15		BALTAY	77	HBC	0	15 $\pi^- p \to \Delta^{++} 3\pi$
2080±40	208	KALELKAR	75	HBC	+	15 $\pi^+ p \to p\pi^+ \rho_3$

[1] Cannot determine spin to be 3.

$X(2000)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
225±50		[2] ARMSTRONG	93D	E760		$\overline{p}p \to 3\pi^0 \to 6\gamma$
~ 500		[2] ANTIPOV	77	CIBS	−	25 $\pi^- p \to p\pi^- \rho_3$
355±21		BALTAY	77	HBC	0	15 $\pi^- p \to \Delta^{++} 3\pi$
340±80	208	KALELKAR	75	HBC	+	15 $\pi^+ p \to p\pi^+ \rho_3$

[2] Cannot determine spin to be 3.

$X(2000)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	
Γ_2	$\rho_3(1690)\pi$	dominant

$X(2000)$ BRANCHING RATIOS

$\Gamma(\rho_3(1690)\pi)/\Gamma(3\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	KALELKAR	75	HBC	+	15 $\pi^+ p \to p3\pi$

$X(2000)$ REFERENCES

ARMSTRONG	93D	PL B307 399	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
BALTAY	77	PRL 39 591	+Cautis, Kalelkar	(COLU) JP
KALELKAR	75	Thesis Nevis 207		(COLU)

OTHER RELATED PAPERS

HARRIS	81	ZPHY C9 275	+Dunn, Lubatti, Moriyasu, Podolsky+	(SEAT, UCB)
HUSON	68	PL 28B 208	+Lubatti, Six, Veillet+	(ORSAY, MILA, UCLA)
DANYSZ	67B	NC 51A 801	+French, Simak	(CERN)

$f_2(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2010)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2011^{+62}_{-76}	[1] ETKIN	88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1980± 20	[2] BOLONKIN	88	SPEC	40 $\pi^- p \to K^0_S K^0_S n$
2050^{+90}_{-50}	ETKIN	85	MPS	22 $\pi^- p \to 2\phi n$
2120^{+20}_{-120}	LINDENBAUM	84	RVUE	
2160± 50	ETKIN	82	MPS	22 $\pi^- p \to 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 98^{+1}_{-3}, 0^{+1}_{-0}, and 2^{+2}_{-1}, respectively.

[2] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
202^{+67}_{-62}	[3] ETKIN	88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
145± 50	[4] BOLONKIN	88	SPEC	40 $\pi^- p \to K^0_S K^0_S n$
200^{+160}_{-50}	ETKIN	85	MPS	22 $\pi^- p \to 2\phi n$
300^{+150}_{-50}	LINDENBAUM	84	RVUE	
310± 70	ETKIN	82	MPS	22 $\pi^- p \to 2\phi n$

[3] Includes data of ETKIN 85.

[4] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2010)$ REFERENCES

BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

OTHER RELATED PAPERS

LANDBERG	96	PR D53 2839	+Adams, Chan+	(BNL, CUNY, RPI)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$f_0(2020)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$f_0(2020)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2020±35	BARBERIS	97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$

$f_0(2020)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
410±50	BARBERIS	97B	OMEG	450 $pp \to pp2(\pi^+\pi^-)$

$f_0(2020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi\pi$	seen

$f_0(2020)$ REFERENCES

BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)

$a_4(2040)$

$I^G(J^{PC}) = 1^-(4^{++})$

$a_4(2040)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2020±16 OUR AVERAGE				
2010±20	[1] DONSKOV 96	GAM2	0	38 $\pi^- p \to \eta\pi^0 n$
2040±30	[2] CLELAND 82B	SPEC	±	50 $\pi p \to K_S^0 K^\pm p$
2030±50	[3] CORDEN 78C	OMEG	0	15 $\pi^- p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1903±10	[4] BALDI 78	SPEC	–	10 $\pi^- p \to p K_S^0 K^-$

[1] From a simultaneous fit to the G_+ and G_0 wave intensities.
[2] From an amplitude analysis.
[3] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[4] From a fit to the Y_8^0 moment. Limited by phase space.

$a_4(2040)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
387± 70 OUR AVERAGE				
370± 80	[5] DONSKOV 96	GAM2	0	38 $\pi^- p \to \eta\pi^0 n$
380±150	[6] CLELAND 82B	SPEC	±	50 $\pi p \to K_S^0 K^\pm p$
510±200	[7] CORDEN 78C	OMEG	0	15 $\pi^- p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
166± 43	[8] BALDI 78	SPEC	–	10 $\pi^- p \to p K_S^0 K^-$

[5] From a simultaneous fit to the G_+ and G_0 wave intensities.
[6] From an amplitude analysis.
[7] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[8] From a fit to the Y_8^0 moment. Limited by phase space.

$a_4(2040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\pi^+\pi^-\pi^0$	seen
Γ_3	$\eta\pi^0$	seen

$a_4(2040)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	BALDI 78	SPEC	±	10 $\pi^- p \to K_S^0 K^- p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	CORDEN 78C	OMEG	0	15 $\pi^- p \to 3\pi n$

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	DONSKOV 96	GAM2	0	38 $\pi^- p \to \eta\pi^0 n$

$a_4(2040)$ REFERENCES

DONSKOV 96 PAN 59 982 +Inyakin, Kachanov+ (GAMS Collab.) IGJPC
Translated from YAF 59 1027.
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
BALDI 78 PL 74B 413 +Bohringer, Dorsaz, Hungerbuhler+ (GEVA) JP
CORDEN 78C NP B136 77 +Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC) JP

OTHER RELATED PAPERS

DELFOSSE 81 NP B183 349 +Guisan, Martin, Muhlemann, Weill+ (GEVA, LAUS)

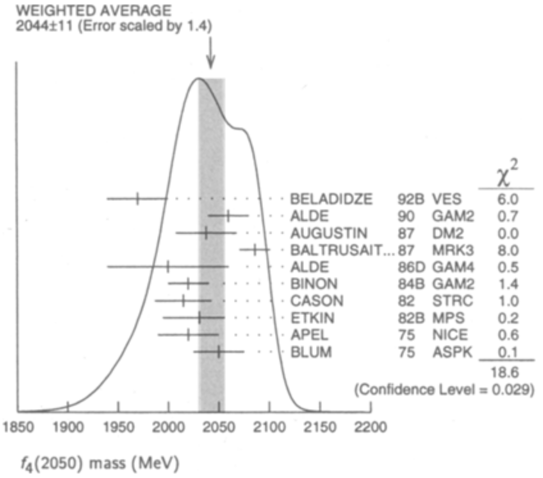
$f_4(2050)$

$I^G(J^{PC}) = 0^+(4^{++})$

$f_4(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2044±11 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
1970±30		BELADIDZE 92B	VES	36 $\pi^- p \to \omega\omega n$
2060±20		ALDE 90	GAM2	38 $\pi^- p \to \omega\omega n$
2038±30		AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
2086±15		BALTRUSAIT...87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
2000±60		ALDE 86D	GAM4	100 $\pi^- p \to n2\eta$
2020±20	40k	[1] BINON 84B	GAM2	38 $\pi^- p \to n2\pi^0$
2015±28		[2] CASON 82	STRC	8 $\pi^+ p \to \Delta^{++}\pi^0\pi^0$
2031^{+25}_{-36}		ETKIN 82B	MPS	23 $\pi^- p \to n2K_S^0$
2020±30	700	APEL 75	NICE	40 $\pi^- p \to n2\pi^0$
2050±25		BLUM 75	ASPK	18.4 $\pi^- p \to nK^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2010		MARTIN 97	RVUE	$\overline{N}N \to \pi\pi$
~ 2040		[3] OAKDEN 94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 1990		[4] OAKDEN 94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
1978± 5		[5] ALPER 80	CNTR	62 $\pi^- p \to K^+K^- n$
2040±10		[5] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
1935±13		[5] CORDEN 79	OMEG	12–15 $\pi^- p \to n2\pi$
1988± 7		EVANGELISTA 79B	OMEG	10 $\pi^- p \to K^+K^- n$
1922±14		[6] ANTIPOV 77	CIBS	25 $\pi^- p \to p3\pi$

[1] From a partial-wave analysis of the data.
[2] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$.
[3] From solution A of amplitude analysis of data on $\overline{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.
[4] From solution B of amplitude analysis of data on $\overline{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.
[5] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[6] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.



$f_4(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
208± 13 OUR AVERAGE	Error includes scale factor of 1.2.			
300± 50		BELADIDZE 92B	VES	36 $\pi^- p \to \omega\omega n$
170± 60		ALDE 90	GAM2	38 $\pi^- p \to \omega\omega n$
304± 60		AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
210± 63		BALTRUSAIT...87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
400±100		ALDE 86D	GAM4	100 $\pi^- p \to n2\eta$
240± 40	40k	[7] BINON 84B	GAM2	38 $\pi^- p \to n2\pi^0$
190± 14		DENNEY 83	LASS	10 $\pi^+ n/\pi^+ p$
186^{+103}_{-58}		[8] CASON 82	STRC	8 $\pi^+ p \to \Delta^{++}\pi^0\pi^0$
305^{+36}_{-119}		ETKIN 82B	MPS	23 $\pi^- p \to n2K_S^0$
180± 60	700	APEL 75	NICE	40 $\pi^- p \to n2\pi^0$
225^{+120}_{-70}		BLUM 75	ASPK	18.4 $\pi^- p \to nK^+K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

~ 200	MARTIN	97	RVUE	$\overline{N}N \to \pi\pi$
~ 60	[9] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 80	[10] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
243± 16	[11] ALPER	80	CNTR	62 $\pi^- p \to K^+ K^- n$
140± 15	[11] ROZANSKA	80	SPRK	18 $\pi^- p \to p\overline{p}n$
263± 57	[11] CORDEN	79	OMEG	12–15 $\pi^- p \to n2\pi$
100± 28	EVANGELISTA	79B	OMEG	10 $\pi^- p \to K^+ K^- n$
107± 56	[12] ANTIPOV	77	CIBS	25 $\pi^- p \to p3\pi$

[7] From a partial-wave analysis of the data.

[8] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$.

[9] From solution A of amplitude analysis of data on $\overline{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[10] From solution B of amplitude analysis of data on $\overline{p}p \to \pi\pi$. See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[11] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.

[12] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	(26 ±6) %
Γ_2	$\pi\pi$	(17.0±1.5) %
Γ_3	$K\overline{K}$	($6.8^{+3.4}_{-1.8}$) × 10^{-3}
Γ_4	$\eta\eta$	(2.1±0.8) × 10^{-3}
Γ_5	$4\pi^0$	< 1.2 %
Γ_6	$\gamma\gamma$	

$f_4(2050)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\qquad$ $\Gamma_3\Gamma_6/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	95	ALTHOFF	85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

$\Gamma(\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\qquad$ $\Gamma_2\Gamma_6/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	95	13 ± 4	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$

$f_4(2050)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma(\pi\pi)$ $\qquad$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.5 ±0.3	ALDE	90	GAM2	38 $\pi^- p \to \omega\omega n$

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ $\qquad$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.170±0.015 OUR AVERAGE				
0.18 ±0.03	[13] BINON	83C	GAM2	38 $\pi^- p \to n4\gamma$
0.16 ±0.03	[13] CASON	82	STRC	8 $\pi^+ p \to \Delta^{++}\pi^0\pi^0$
0.17 ±0.02	[13] CORDEN	79	OMEG	12–15 $\pi^- p \to n2\pi$

[13] Assuming one pion exchange.

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ $\qquad$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 $^{+0.02}_{-0.01}$	ETKIN	82B	MPS	23 $\pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ $\qquad$ Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.1±0.8	ALDE	86D	GAM4	100 $\pi^- p \to n4\gamma$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ $\qquad$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.012	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$f_4(2050)$ REFERENCES

MARTIN	97	PR C56 1114	B.R. Martin, Oades	(LOUC, AARH)
KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)
BELADIDZE	92B	ZPHY C54 367	+Bityukov, Borisov+	(VES Collab.)
ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BINON	84B	LNC 39 41	+Donskov, Duteil, Gouanere+	(SERP, BELG, LAPP)
BINON	83C	SJNP 38 723 Translated from YAF 38 1199.	+Gouanere, Donskov, Duteil+	(SERP, BRUX+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
APEL	75	PL 57B 398	+Augenstein+	(KARLK, KARLE, PISA, SERP, WIEN, CERN) JP
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP

OTHER RELATED PAPERS

PROKOSHKIN	97	SPD 42 117 Translated from DANS 353 323.	+Kondashov, Sadovsky+	(SERP)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
GOTTESMAN	80	PR D22 1503	+Jacobs+	(SYRA, BRAN, BNL, CINC)
WAGNER	74	London Conf. 2 27		(MPIM)

$f_0(2060)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$f_0(2060)$ MASS

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2050	[1] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 2060	[2] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$

[1] From solution A of amplitude analysis of data on $\overline{p}p \to \pi\pi$ See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[2] From solution B of amplitude analysis of data on $\overline{p}p \to \pi\pi$ See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

$f_0(2060)$ WIDTH

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 120	[3] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 50	[4] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$

[3] From solution A of amplitude analysis of data on $\overline{p}p \to \pi\pi$ See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[4] From solution B of amplitude analysis of data on $\overline{p}p \to \pi\pi$ See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

$f_0(2060)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-$	seen

$f_0(2060)$ REFERENCES

KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)

$\pi_2(2100)$

$I^G(J^{PC}) = 1^-(2^{-+})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$\pi_2(2100)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2090± 29 OUR AVERAGE				
2090± 30	[1] AMELIN	95B	VES	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
2100±150	[2] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[1] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $(\pi\pi)_S\pi$ waves.

[2] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
625± 50 OUR AVERAGE Error includes scale factor of 1.2.				
520±100	[3] AMELIN	95B	VES	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
651± 50	[4] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[3] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $(\pi\pi)_S\pi$ waves.

[4] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	seen
Γ_2	$\rho\pi$	seen
Γ_3	$f_2(1270)\pi$	seen
Γ_4	$(\pi\pi)_S\pi$	seen

$\pi_2(2100)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(3\pi)$ **Γ_2/Γ_1**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.19±0.05	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_2(1270)\pi)/\Gamma(3\pi)$ **Γ_3/Γ_1**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.36±0.09	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma((\pi\pi)_S\pi)/\Gamma(3\pi)$ **Γ_4/Γ_1**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.45±0.07	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

D-wave/S-wave RATIO FOR $\pi_2(2100) \to f_2(1270)\pi$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.39±0.23	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

[5] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ REFERENCES

AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$f_2(2150)$

$I^G(J^{PC}) = 0^+(2^{++})$

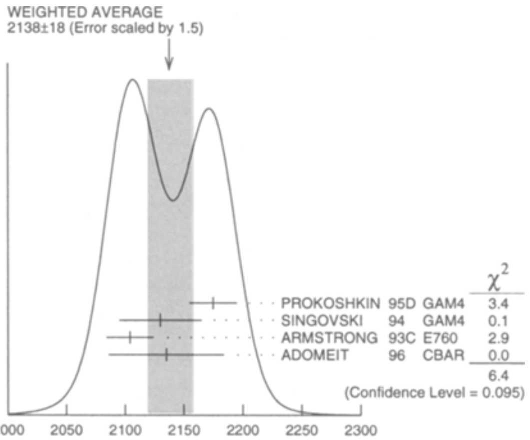
OMITTED FROM SUMMARY TABLE

This entry was previously called T_0.

$f_2(2150)$ MASS

$f_2(2150)$ MASS, COMBINED MODES (MeV)

VALUE (MeV)	*DOCUMENT ID*
2138±18 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.5. See the ideogram below.

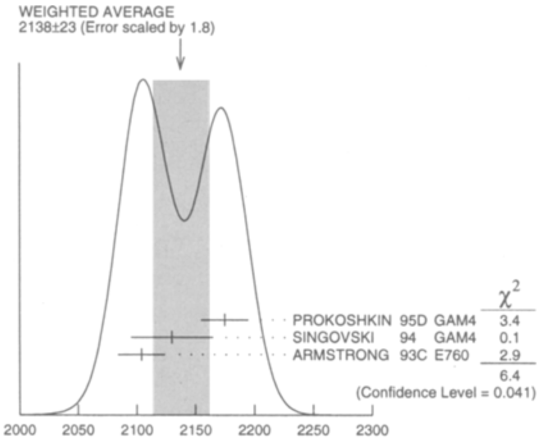


$f_2(2150)$ MASS, COMBINED MODES (MeV)

$\eta\eta$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
The data in this block is included in the average printed for a previous datablock.				
2138±23 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.				
2175±20	PROKOSHKIN	95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp2\eta$
2130±35	SINGOVSKI	94	GAM4	450 $pp \to pp2\eta$
2104±20	[1] ARMSTRONG	93C	E760	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$

[1] No J^{PC} determination.



$f_2(2150)$ MASS, $\eta\eta$ MODE (MeV)

$\eta\pi\pi$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2135±20±45	ADOMEIT 96	CBAR	0	1.94 $\overline{p}p \to \eta 3\pi^0$

$\overline{p}p \to \pi\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 2226	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 2090	[2] OAKDEN 94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 2120	[3] OAKDEN 94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 2170	[4] MARTIN 80B	RVUE	
~ 2150	[4] MARTIN 80C	RVUE	
~ 2150	[5] DULUDE 78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[2] OAKDEN 94 makes an amplitude analysis of LEAR data on $\overline{p}p \to \pi\pi$ using a method based on Barrelet zeros. This is solution A. The amplitude analysis of HASAN 94 includes earlier data as well, and assume that the data can be parametrized in terms of towers of nearly degenerate resonances on the leading Regge trajectory. See also KLOET 96 and MARTIN 97 who make related analyses.

[3] From solution B of amplitude analysis of data on $\overline{p}p \to \pi\pi$.

[4] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[5] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$, $\overline{N}N$ or $\overline{K}K$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
$2139^{+\ 8}_{-\ 9}$	[6] EVANGELISTA 97	SPEC		0.6-2.4 $\overline{p}p \to K^0_S K^0_S$
~ 2190	[7] CUTTS 78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155±15	[7,8] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193± 2	[7,9] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel

[6] Isospin 0 and 2 not separated.

[7] Isospins 0 and 1 not separated.

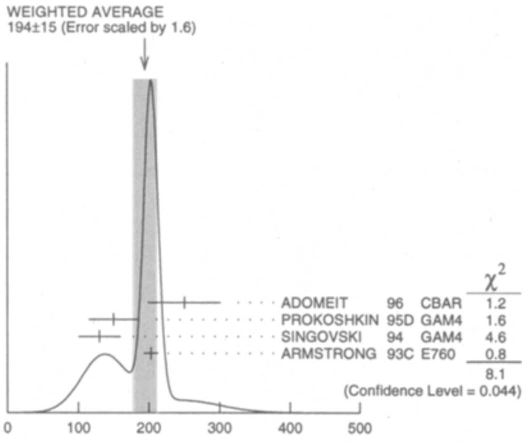
[8] From a fit to the total elastic cross section.

[9] Referred to as T or T region by ALSPECTOR 73.

$f_2(2150)$ WIDTH

$f_2(2150)$ WIDTH, COMBINED MODES (MeV)

VALUE (MeV)	DOCUMENT ID
194±15 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.6. See the ideogram below.



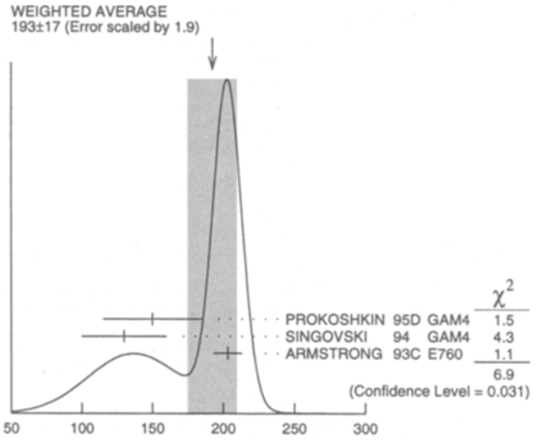
$f_2(2150)$ WIDTH, COMBINED MODES (MeV)

$\eta\eta$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
193±17 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.		
150±35	PROKOSHKIN 95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp 2\eta$
130±30	SINGOVSKI 94	GAM4	450 $pp \to pp 2\eta$
203±10	[10] ARMSTRONG 93C	E760	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$

[10] No J^{PC} determination.



$f_2(2150)$ WIDTH, $\eta\eta$ MODE (MeV)

$\eta\pi\pi$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
250±25±45	ADOMEIT 96	CBAR	0	1.94 $\overline{p}p \to \eta 3\pi^0$

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
250 OUR ESTIMATE			

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 226	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 70	[11] OAKDEN 94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 250	[12] MARTIN 80B	RVUE	
~ 250	[12] MARTIN 80C	RVUE	
~ 250	[13] DULUDE 78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[11] See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[12] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[13] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$, $\overline{N}N$ or $\overline{K}K$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
56^{+31}_{-16}	[14] EVANGELISTA 97	SPEC		0.6-2.4 $\overline{p}p \to K^0_S K^0_S$
135±75	[15,16] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98± 8	[16] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel

[14] Isospin 0 and 2 not separated.

[15] From a fit to the total elastic cross section.

[16] Isospins 0 and 1 not separated.

$f_2(2150)$ DECAY MODES

	Mode
Γ_1	$\pi\pi$
Γ_2	$\eta\eta$
Γ_3	$K\overline{K}$
Γ_4	$f_2(1270)\eta$
Γ_5	$a_2(1320)\pi$

$f_2(2150)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\eta)$ Γ_3/Γ_2

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.1	95	[17] PROKOSHKIN 95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp 2\eta$

[17] Using data from ARMSTRONG 89D.

$\Gamma(\pi\pi)/\Gamma(\eta\eta)$ Γ_1/Γ_2

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.33	95	[18] PROKOSHKIN 95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp 2\eta$

[18] Derived from a $\pi^0\pi^0/\eta\eta$ limit.

$\Gamma(f_2(1270)\eta)/\Gamma(a_2(1320)\pi)$ Γ_4/Γ_5

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.79±0.11	[19] ADOMEIT	96	CBAR	1.94 $\overline{p}p \to \eta 3\pi^0$

[19] Using $B(a_2(1320) \to \eta\pi) = 0.145$

$f_2(2150)$ REFERENCES

EVANGELISTA	97	PR D56 3803	C. Evangelista, Palano, Drijard+	(LEAR Collab.)
MARTIN	97	PR C56 1114	B.R. Martin, Oades	(LOUC, AARH)
ADOMEIT	96	ZPHY C71 227	+Amsler, Armstrong+	(Crystal Barrel Collab.)
KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
PROKOSHKIN	95D	SPD 40 495 Translated from DANS 344 469.		(SERP) IGJPC
HASAN	94	PL B334 215	+Bugg	(LOQM)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)
SINGOVSKI	94	NC 107 1911		(SERP)
ARMSTRONG	93C	PL B307 394	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)

OTHER RELATED PAPERS

FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)

$\rho(2150)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $T_1(2190)$.

$\rho(2150)$ MASS

$e^+e^- \to \pi^+\pi^-, K^+K^-, 6\pi$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2149±17 OUR AVERAGE	Includes data from the datablock that follows this one.				
2153±37	BIAGINI	91	RVUE		$e^+e^- \to \pi^+\pi^-, K^+K^-$
2110±50	[2] CLEGG	90	RVUE	0	$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$

$\overline{p}p \to \pi\pi$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2191	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 1988	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 2070	[1] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 2170	[3] MARTIN	80B	RVUE	
~ 2100	[3] MARTIN	80C	RVUE	

[1] See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190	[4] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155±15	[4,5] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2190±10	[7] ABRAMS	70	CNTR		S channel $\overline{p}N$

$\pi^-p \to \omega\pi^0n$

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2155±21 OUR AVERAGE				
2140±30	ALDE	95	GAM2	38 $\pi^-p \to \omega\pi^0n$
2170±30	ALDE	92C	GAM4	100 $\pi^-p \to \omega\pi^0n$

[2] Includes ATKINSON 85.

[3] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[4] Isospins 0 and 1 not separated.

[5] From a fit to the total elastic cross section.

[6] Referred to as T or T region by ALSPECTOR 73.

[7] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho(2150)$ WIDTH

$e^+e^- \to \pi^+\pi^-, K^+K^-, 6\pi$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
363± 50 OUR AVERAGE	Includes data from the datablock that follows this one.				
389± 79	BIAGINI	91	RVUE		$e^+e^- \to \pi^+\pi^-, K^+K^-$
410±100	[9] CLEGG	90	RVUE	0	$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$

$\overline{p}p \to \pi\pi$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 296	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 244	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 40	[8] OAKDEN	94	RVUE	0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 250	[10] MARTIN	80B	RVUE	
~ 200	[10] MARTIN	80C	RVUE	

[8] See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135±75	[11,12] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98± 8	[12] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
~ 85	[13] ABRAMS	70	CNTR		S channel $\overline{p}N$

$\pi^-p \to \omega\pi^0n$

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
320±70	ALDE	95	GAM2	38 $\pi^-p \to \omega\pi^0n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 300	ALDE	92C	GAM4	100 $\pi^-p \to \omega\pi^0n$

[9] Includes ATKINSON 85.

[10] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[11] From a fit to the total elastic cross section.

[12] Isospins 0 and 1 not separated.

[13] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho(2150)$ REFERENCES

KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
ALDE	95	ZPHY C66 379	+Binon, Bricman+	(GAMS Collab.) JP
HASAN	94	PL B334 215	+Bugg	(LOQM)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)
ALDE	92C	ZPHY C54 553	+Bencheikh, Binon+	(BELG, SERP, KEK, LANL, LAPP)
BIAGINI	91	NC 104A 363	+Dubnicka+	(FRAS, PRAG)
CLEGG	90	ZPHY C45 677	+Donnachie	(LANC, MCHS)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_0(2200)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the $K^0_S K^0_S$ system. Not seen in Υ radiative decays (BARU 89). Needs confirmation.

$f_0(2200)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2197±17	[1] AUGUSTIN	88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2122	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$
~ 2321	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$

[1] Cannot determine spin to be 0.

$f_0(2200)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
201±51	[2] AUGUSTIN	88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 273	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$
~ 223	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$

[2] Cannot determine spin to be 0.

$f_0(2200)$ REFERENCES

HASAN	94	PL B334 215	+Bugg	(LOQM)
BARU	89	ZPHY C42 505	+Beilin, Blinov, Blinov+	(NOVO)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)

$\boxed{f_J(2220)}$

$I^G(J^{PC}) = 0^+(2^{++} \text{ or } 4^{++})$

OMITTED FROM SUMMARY TABLE

THE $f_J(2220)$

Written March 1998 by M. Doser (CERN).

This state has been seen in $J/\psi(1S)$ radiative decay into $K\overline{K}$ (K^+K^- and $K^0_S K^0_S$ modes seen (BALTRUSAITIS 86D, BAI 96B)). An upper limit from DM2 for these modes (AUGUSTIN 88) is at the level at which observation is claimed. There are also indications for further decay modes ($\pi^+\pi^-$ and $\overline{p}p$) in the same production process (BAI 96B), although again at the level at which previous upper limits had been obtained (BALTRUSAITIS 86D); also seen in $\eta\eta$ (ALDE 86B), $K^0_S K^0_S$ (ASTON 88D) and in K^+K^- (ALDE 88F), albeit with very low statistics. Its J^{PC} is determined from the angular distributions of these observations.

It is not seen in Υ radiative decays (BARU 89), B inclusive decays (BEHRENDS 84), nor in $\gamma\gamma$ (GODANG 97). It is also not seen in formation in $\overline{p}p \rightarrow K^+K^-$ (BARDIN 87, SCULLI 87), in $\overline{p}p \rightarrow K_S K_S$ (BARNES 93, EVANGELISTA 97), nor in $\overline{p}p \rightarrow \pi^+\pi^-$ (HASAN 96). The upper limit in $\overline{p}p$ formation can be related to the claimed decay into $\overline{p}p$ to give a lower limit for the process $J/\psi(1S) \rightarrow \gamma f_J(2220)$ of $\sim 2.5 \times 10^{-3}$. Such a signal should be visible in the inclusive photon spectrum (BLOOM 82). The limit also leads to the conclusion that two-body final states constitute only a small fraction of all decay modes of the $f_J(2220)$. Observation of further decay modes would be very desirable.

$f_J(2220)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2231.1± 3.5 OUR AVERAGE				
2235 ± 4 ± 6	74	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma\pi^+\pi^-$
2230 $^{+6}_{-7}$ ±16	46	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma K^+K^-$
2232 $^{+8}_{-7}$ ±15	23	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma K^0_S K^0_S$
2235 ± 4 ± 5	32	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma p\overline{p}$
2209 $^{+17}_{-15}$ ±10		ASTON 88F	LASS	11 $K^-p \rightarrow K^+K^-\Lambda$
2230 ±20		BOLONKIN 88	SPEC	40 $\pi^-p \rightarrow K^0_S K^0_S n$
2220 ±10	41	[1] ALDE 86B	GA24	38–100 $\pi p \rightarrow n\eta\eta'$
2230 ± 6 ±14	93	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^+K^-$
2232 ± 7 ± 7	23	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^0_S K^0_S$

[1] ALDE 86B uses data from both the GAMS-2000 and GAMS-4000 detectors.

$f_J(2220)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
23^{+8}_{-7} OUR AVERAGE				
19^{+13}_{-11}±12	74	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma\pi^+\pi^-$
20^{+20}_{-15}±17	46	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma K^+K^-$
20^{+25}_{-16}±14	23	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma K^0_S K^0_S$
15^{+12}_{-9}± 9	32	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma p\overline{p}$
60^{+107}_{-57}		ASTON 88F	LASS	11 $K^-p \rightarrow K^+K^-\Lambda$
80± 30		BOLONKIN 88	SPEC	40 $\pi^-p \rightarrow K^0_S K^0_S n$
26^{+20}_{-16}±17	93	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^+K^-$
18^{+23}_{-15}±10	23	BALTRUSAIT...86D	MRK3	$e^+e^- \rightarrow \gamma K^0_S K^0_S$

$f_J(2220)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	$\pi^+\pi^-$	seen
Γ_3	$K\overline{K}$	seen
Γ_4	$p\overline{p}$	seen
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\eta\eta'(958)$	seen

$f_J(2220)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_3\Gamma_5/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
< 5.6	95	[2] GODANG 97	CLE2	$\gamma\gamma \rightarrow K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 86	95	[2] ALBRECHT 90G	ARG	$\gamma\gamma \rightarrow K^+K^-$
<1000	95	[3] ALTHOFF 85B	TASS	$\gamma\gamma$, $K\overline{K}\pi$

[2] Assuming $J^P = 2^+$.

[3] True for $J^P = 0^+$ and $J^P = 2^+$.

$f_J(2220)$ $\Gamma(i)\Gamma(\overline{p}p)/\Gamma(\text{total})$

$\Gamma(p\overline{p}) \times \Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ $\Gamma_4\Gamma_2/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<3.9	99	[4] HASAN 96	SPEC	$\overline{p}p \rightarrow \pi^-\pi^+$

[4] Assuming $\Gamma = 15$ MeV and $J^P = 2^+$

$f_J(2220)$ BRANCHING RATIOS

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.0	95	[5] EVANGELISTA 97	SPEC	1.96-2.40$\overline{p}p \rightarrow K^0_S K^0_S$
<1.1	99.7	[6] BARNES 93	SPEC	1.3-1.57$\overline{p}p \rightarrow K^0_S K^0_S$
<2.6	99.7	[6] BARDIN 87	CNTR	1.3-1.5$\overline{p}p \rightarrow K^+K^-$
<3.6	99.7	[6] SCULLI 87	CNTR	1.29-1.55$\overline{p}p \rightarrow K^+K^-$

[5] Assuming $\Gamma \sim 20$ MeV, $J^P = 2^+$ and B($f_J(2220) \rightarrow K\overline{K}$) = 100%.

[6] Assuming $\Gamma = 30$-35 MeV, $J^P = 2^+$ and B($f_J(2220) \rightarrow K\overline{K}$) = 100%.

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ Γ_1/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
1.0±0.5	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma 2\pi, K\overline{K}$

$\Gamma(p\overline{p})/\Gamma(K\overline{K})$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.17±0.09	BAI 96B	BES	$e^+e^- \rightarrow J/\psi \rightarrow \gamma p\overline{p}, K\overline{K}$

$f_J(2220)$ REFERENCES

EVANGELISTA	97	PR D56 3803	C. Evangelista, Palano, Drijard+	(LEAR Collab.)
GODANG	97	PRL 79 3829	R. Godang, Kinoshita, Lai+	(CLEO Collab.)
BAI	96B	PRL 76 3502	+Chen, Chen+	(BES Collab.)
HASAN	96	PL B388 376	+Bugg	(BRUN, LOQM)
BARNES	93	PL B309 469	+Birien, Breunlich	(PS185 Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
ASTON	88F	PL B215 199	+Awaji+	(SLAC, NAGO, CINC, INUS) JP
BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
BARDIN	87	PL B195 292	+Burgun+	(SACL, FERR, CERN, PADO, TORI)
SCULLI	87	PRL 58 1715	+Christenson, Kreiter, Nemethy, Yamin	(NYU, BNL)
ALDE	86B	PL B177 120	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)

OTHER RELATED PAPERS

HUANG	96	PL B380 189	+Jin, Zhang, Chao	(BHEP, BEIJ)
BARDIN	87	PL B195 292	+Burgun+	(SACL, FERR, CERN, PADO, TORI)
YAOUANC	85	ZPHY C28 309	+Oliver, Pene, Raynal, Ono	(ORSAY, TOKY)
GODFREY	84	PL 141B 439	+Kokoski, Isgur	(TNTO)
SHATZ	84	PL 138B 209		(CIT)
WILLEY	84	PRL 52 585		(PITT)

$\boxed{\eta(2225)}$ $I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in $J/\psi \to \gamma\phi\phi$. Needs confirmation.

$\eta(2225)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$2230\pm25\pm15$	BAI 90B	MRK3	$J/\psi \to \gamma K^+ K^- K^+ K^-$
$2214\pm20\pm13$	BAI 90B	MRK3	$J/\psi \to \gamma K^+ K^- K^0_S K^0_L$
~ 2220	BISELLO 86B	DM2	$J/\psi \to \gamma K^+ K^- K^+ K^-$

$\eta(2225)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{150^{+300}_{-60}\pm60}$	BAI 90B	MRK3	$J/\psi \to \gamma K^+ K^- K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 80	BISELLO 86B	DM2	$J/\psi \to \gamma K^+ K^- K^+ K^-$

$\eta(2225)$ REFERENCES

BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)

$\boxed{\rho_3(2250)}$ $I^G(J^{PC}) = 1^+(3^{--})$

OMITTED FROM SUMMARY TABLE

Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $f_4(2300)$, $\rho_5(2350)$.

$\rho_3(2250)$ MASS

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2232	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 2007	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 2090	[1] OAKDEN 94	RVUE		0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 2250	[2] MARTIN 80B	RVUE		
~ 2300	[2] MARTIN 80C	RVUE		
~ 2140	[3] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 2150	[4] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

[1] See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[2] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[3] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.

[4] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2190	[5] CUTTS 78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155 ± 15	[5,6] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
$2193\pm\ 2$	[5,7] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
2190 ± 10	[8] ABRAMS 70	CNTR		S channel $\overline{p}N$

[5] Isospins 0 and 1 not separated.

[6] From a fit to the total elastic cross section.

[7] Referred to as T or T region by ALSPECTOR 73.

[8] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ WIDTH

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 220	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 287	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 60	[9] OAKDEN 94	RVUE		0.36–1.55 $\overline{p}p \to \pi^+\pi^-$
~ 250	[10] MARTIN 80B	RVUE		
~ 200	[10] MARTIN 80C	RVUE		
~ 150	[11] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 200	[12] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

[9] See however KLOET 96 who find waves only up to $J = 3$ to be important but not significantly resonant.

[10] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[11] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.

[12] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
135 ± 75	[13,14] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
$98\pm\ 8$	[14] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
~ 85	[15] ABRAMS 70	CNTR		S channel $\overline{p}N$

[13] From a fit to the total elastic cross section.

[14] Isospins 0 and 1 not separated.

[15] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ REFERENCES

KLOET	96	PR D53 6120	+Myhrer	(RUTG, NORD)
HASAN	94	PL B334 215	+Bugg	(LOQM)
OAKDEN	94	NPA 574 731	+Pennington	(DURH)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
ZEMANY	76	NP B103 537	+MingMa, Mountz, Smith	(MSU)
BERTANZA	74	NC 23A 209	+Bigi, Casali, Lariccia+	(PISA, PADO, TORI)
BETTINI	73	NC 15A 563	+Alston-Garnjost, Bigi+	(PADO, LBL, PISA, TORI)
DONNACHIE	73	LNC 7 285	+Thomas	(MCHS)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$\boxed{f_2(2300)}$ $I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2300)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{2297\pm28}$	[1] ETKIN 88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2231 ± 10	BOOTH 86	OMEG	85 π^- Be $\to 2\phi$Be
2220^{+90}_{-20}	LINDENBAUM 84	RVUE	
2320 ± 40	ETKIN 82	MPS	22 $\pi^- p \to 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 6^{+15}_{-5}, 25^{+18}_{-14}, and 69^{+16}_{-27}, respectively.

$f_2(2300)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{149\pm41}$	[2] ETKIN 88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
133 ± 50	BOOTH 86	OMEG	85 π^- Be $\to 2\phi$Be
200 ± 50	LINDENBAUM 84	RVUE	
220 ± 70	ETKIN 82	MPS	22 $\pi^- p \to 2\phi n$

[2] Includes data of ETKIN 85.

f_2(2300) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

f_2(2300) REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)

OTHER RELATED PAPERS

LANDBERG	96	PR D53 2839	+Adams, Chan+	(BNL, CUNY, RPI)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

f_4(2300)

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_0(2350)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N$(1100–3600) entry. See also ρ(2150), f_2(2150), ρ_3(2250), ρ_5(2350).

f_4(2300) MASS

$\overline{p}p \to \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2314	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 2300	[1] MARTIN	80B	RVUE	
~ 2300	[1] MARTIN	80C	RVUE	
~ 2340	[2] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 2330	DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$
~ 2310	[3] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \to \pi\pi$

[1] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[3] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2380	[4] CUTTS	78B	CNTR	0.97–3 $\overline{p}p \to \overline{N}N$
2345±15	[4,5] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \to \overline{p}p$
2359± 2	[4,6] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
2375±10	ABRAMS	70	CNTR	S channel $\overline{N}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as U or U region by ALSPECTOR 73.

f_4(2300) WIDTH

$\overline{p}p \to \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 278	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 200	[7] MARTIN	80C	RVUE	
~ 150	[8] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 210	[9] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \to \pi\pi$

[7] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[8] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[9] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
135^{+150}_{-65}	[10,11] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \to \overline{p}p$
165^{+18}_{-8}	[11] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
~ 190	ABRAMS	70	CNTR	S channel $\overline{N}N$

[10] From a fit to the total elastic cross section.
[11] Isospins 0 and 1 not separated.

f_4(2300) REFERENCES

HASAN	94	PL B334 215	+Bugg	(LOQM)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

OTHER RELATED PAPERS

FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)

f_2(2340)

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

f_2(2340) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2339±55	[1] ETKIN	88	MPS	22 $\pi^-p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2392±10	BOOTH	86	OMEG	85 π^-Be $\to 2\phi$Be
2360±20	LINDENBAUM	84	RVUE	

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 37 ± 19, 4^{+12}_{-4}, and 59^{+21}_{-19}, respectively.

f_2(2340) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{319^{+81}_{-69}}$	[2] ETKIN	88	MPS	22 $\pi^-p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
198± 50	BOOTH	86	OMEG	85 π^-Be $\to 2\phi$Be
150^{+150}_{-50}	LINDENBAUM	84	RVUE	

[2] Includes data of ETKIN 85.

f_2(2340) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

f_2(2340) REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)

OTHER RELATED PAPERS

LANDBERG	96	PR D53 2839	+Adams, Chan+	(BNL, CUNY, RPI)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$\rho_5(2350)$

$I^G(J^{PC}) = 1^+(5^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_1(2400)$. See also the $\overline{N}N(1100\text{–}3600)$ and $X(1900\text{–}3600)$ entries. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$.

$\rho_5(2350)$ MASS

$\pi^- p \to \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2330±35	ALDE 95	GAM2	38 $\pi^- p \to \omega\pi^0 n$

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 2303	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 2300	[1] MARTIN 80B	RVUE		
~ 2250	[1] MARTIN 80C	RVUE		
~ 2500	[2] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 2480	[3] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

S-CHANNEL $\overline{N}N$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 2380	[4] CUTTS 78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2345±15	[4,5] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2359± 2	[4,6] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
2350±10	[7] ABRAMS 70	CNTR		S channel $\overline{N}N$
2360±25	[8] OH 70B	HDBC	−0	$\overline{p}(pn)$, $K^*K2\pi$

[1] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[2] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.

[3] $I(J^P) = 1(5^-)$ from amplitude analysis.

[4] Isospins 0 and 1 not separated.

[5] From a fit to the total elastic cross section.

[6] Referred to as U or U region by ALSPECTOR 73.

[7] For $I = 1$ $\overline{N}N$.

[8] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ WIDTH

$\pi^- p \to \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
400±100	ALDE 95	GAM2	38 $\pi^- p \to \omega\pi^0 n$

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 169	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 250	[9] MARTIN 80B	RVUE		
~ 300	[9] MARTIN 80C	RVUE		
~ 150	[10] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 210	[11] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

S-CHANNEL $\overline{N}N$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
135^{+150}_{-65}	[12,13] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
165^{+18}_{-8}	[13] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
< 60	[14] OH 70B	HDBC	−0	$\overline{p}(pn)$, $K^*K2\pi$
~ 140	ABRAMS 67C	CNTR		S channel $\overline{p}N$

[9] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[10] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.

[11] $I(J^P) = 1(5^-)$ from amplitude analysis.

[12] From a fit to the total elastic cross section.

[13] Isospins 0 and 1 not separated.

[14] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ REFERENCES

ALDE 95 ZPHY C66 379 +Binon, Bricman+ (GAMS Collab.) JP
HASAN 94 PL B334 215 +Bugg (LOQM)
MARTIN 80B NP B176 355 +Morgan (LOUC, RHEL) JP
MARTIN 80C NP B169 216 +Pennington (DURH) JP
CARTER 78B NP B141 467 (LOQM)
CUTTS 78B PR D17 16 +Good, Grannis, Green, Lee+ (STON, WISC)
CARTER 77 PL 67B 117 +Coupland, Eisenhandler, Astbury+ (LOQM, RHEL) JP
COUPLAND 77 PL 71B 460 +Eisenhandler, Gibson, Astbury+ (LOQM, RHEL)
ALSPECTOR 73 PRL 30 511 +Cohen, Cvijanovich+ (RUTG, UPNJ)
OH 73 NP B51 57 +Eastman, MingMa, Parker, Smith+ (MSU)
CHAPMAN 71B PR D4 1275 +Green, Lys, Murphy, Ring+ (MICH)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)
OH 70B PRL 24 1257 +Parker, Eastman, Smith, Sprafka, Ma (MSU)
ABRAMS 67C PRL 18 1209 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)

OTHER RELATED PAPERS

CASO 70 LNC 3 707 +Conte, Tomasini+ (GENO, HAMB, MILA, SACL)
BRICMAN 69 PL 29B 451 +Ferro-Luzzi, Bizard+ (CERN, CAEN, SACL)

$a_6(2450)$

$I^G(J^{PC}) = 1^-(6^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$a_6(2450)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2450±130	[1] CLELAND 82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[1] From an amplitude analysis.

$a_6(2450)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
400±250	[2] CLELAND 82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[2] From an amplitude analysis.

$a_6(2450)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$

$a_6(2450)$ REFERENCES

CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)

$f_6(2510)$

$I^G(J^{PC}) = 0^+(6^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$f_6(2510)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2510±30	BINON 84B	GAM2	38 $\pi^- p \to n2\pi^0$

$f_6(2510)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
240±60	BINON 84B	GAM2	23 $\pi^- p \to n2\pi^0$

$f_6(2510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	(6.0±1.0) %

$f_6(2510)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID	TECN	COMMENT
0.06 ±0.01	[1] BINON 83C	GAM2	38 $\pi^- p \to n4\gamma$

[1] Assuming one pion exchange and using data of BOLOTOV 74.

$f_6(2510)$ REFERENCES

BINON 84B LNC 39 41 +Donskov, Duteil, Gouanere+ (SERP, BELG, LAPP) JP
BINON 83C SJNP 38 723 +Gouanere, Donskov, Duteil+ (SERP, BRUX+)
Translated from YAF 38 1199.
BOLOTOV 74 PL 52B 489 +Isakov, Kakauridze, Khaustov+ (SERP)

$X(3250)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several final states with hidden strangeness ($\Lambda \overline{p} K^+$, $\Lambda \overline{p} K^+ \pi^\pm$, $K^0 p \overline{p} K^\pm$). Needs confirmation.

$X(3250)$ MASS

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3250±8±20	ALEEV 93	BIS2	$X(3250) \to \Lambda \overline{p} K^+$
3265±7±20	ALEEV 93	BIS2	$X(3250) \to \overline{\Lambda} p K^-$

4-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3245±8±20	ALEEV 93	BIS2	$X(3250) \to \Lambda \overline{p} K^+ \pi^\pm$
3250±9±20	ALEEV 93	BIS2	$X(3250) \to \overline{\Lambda} p K^- \pi^\mp$
3270±8±20	ALEEV 93	BIS2	$X(3250) \to K^0_S p \overline{p} K^\pm$

$X(3250)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
45±18	ALEEV 93	BIS2	$X(3250) \to \Lambda \overline{p} K^+$
40±18	ALEEV 93	BIS2	$X(3250) \to \overline{\Lambda} p K^-$

4-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
25±11	ALEEV 93	BIS2	$X(3250) \to \Lambda \overline{p} K^+ \pi^\pm$
50±20	ALEEV 93	BIS2	$X(3250) \to \overline{\Lambda} p K^- \pi^\mp$
25±11	ALEEV 93	BIS2	$X(3250) \to K^0_S p \overline{p} K^\pm$

$X(3250)$ DECAY MODES

	Mode
Γ_1	$\Lambda \overline{p} K^+$
Γ_2	$\Lambda \overline{p} K^+ \pi^\pm$
Γ_3	$K^0 p \overline{p} K^\pm$

$X(3250)$ REFERENCES

ALEEV 93 PAN 56 1358 +Balandin+ (BIS-2 Collab.)
Translated from YAF 56 100.

OTHER LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

$e^+e^-(1100–2200)$

$I^G(J^{PC}) = ?^?(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry contains unflavored vector mesons coupled to e^+e^- (photon) between the ϕ and $J/\psi(1S)$ mass regions. See also $\omega(1420)$, $\rho(1450)$, $\omega(1600)$, $\phi(1680)$, and $\rho(1700)$.

$e^+e^-(1100–2200)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	DOCUMENT ID
1100 to 2200 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1097.0^{+16.0}_{-19.0}$	BARTALUCCI 79	OSPK	$7\ \gamma p \to e^+e^-p$
$31.0^{+24.0}_{-20.0}$	BARTALUCCI 79	OSPK	$7\ \gamma p \to e^+e^-p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1266.0± 5.0	BARTALUCCI 79	DASP	0	$7\ \gamma p \to e^+e^-p$
110.0±35.0	BARTALUCCI 79	DASP	0	$7\ \gamma p \to e^+e^-p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 1830.0	PETERSON 78	SPEC	$\gamma p \to K^+K^-p$
~ 120.0	PETERSON 78	SPEC	$\gamma p \to K^+K^-p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1870±10	ANTONELLI 96	SPEC	$e^+e^- \to$ hadrons
10± 5	ANTONELLI 96	SPEC	$e^+e^- \to$ hadrons

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 2130	[1] ESPOSITO 78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$
~ 30	[1] ESPOSITO 78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$

[1] Not seen by DELCOURT 79.

$e^+e^-(1100–2200)$ REFERENCES

ANTONELLI 96 PL B365 427 +Baldini, Bertani+ (FENICE Collab.)
BARTALUCCI 79 NC 49A 207 +Basini, Bertolucci+ (DESY, FRAS)
DELCOURT 79 PL 86B 395 +Derado, Bertrand, Bisello, Bizot, Buon+ (LALO)
ESPOSITO 78 LNC 22 305 +Felicetti (FRAS, NAPL, PADO, ROMA)
PETERSON 78 PR D18 3955 +Dixon, Ehrlich, Galik, Larson (CORN, HARV)

OTHER RELATED PAPERS

BACCI 76 PL 64B 356 +Bidoli, Penso, Stella, Baldini+ (ROMA, FRAS)
BACCI 75 PL 58B 481 +Bidoli, Penso, Stella+ (ROMA, FRAS)

$\overline{N}N(1100–3600)$

OMITTED FROM SUMMARY TABLE

This entry contains various high mass, unflavored structures coupled to the baryon-antibaryon system, as well as quasi-nuclear bound states below threshold.

$\overline{N}N(1100–3600)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits etc.

VALUE (MeV)	DOCUMENT ID
1100 to 3600 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1107±4	DAFTARI 87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$
111±8±15	DAFTARI 87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1167 ±7	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1191.0±9.9	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1210 ±5.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1325 ±5	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1329.2±7.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1390.9±6.3	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1395	[1,3,4,5] PAVLOPO... 78	CNTR		Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 1410	BETTINI 66	DBC	0	0. $\overline{p}N \to 5\pi$
~ 100	BETTINI 66	DBC	0	0. $\overline{p}N \to 5\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1468± 6	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
88±18	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1512 ± 7	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1523.8± 3.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1522 ± 7	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$
59 ±12	[6] BRIDGES 86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1577.8± 3.4	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
1594 ± 9	[6] BRIDGES 86B	DBC	–	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
81 ±12	[6] BRIDGES 86B	DBC	–	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1633.6±4.1	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$
$1637.1^{+5.6}_{-7.3}$	ADIELS 84	CNTR		$\overline{p}$He

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1638±3.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1644.0^{+5.6}_{-7.3}$	ADIELS 84	CNTR	$\overline{p}$He

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1646	[1,3,4,5] PAVLOPO... 78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1687.1^{+5.0}_{-4.3}$	ADIELS 84	CNTR	$\overline{p}$He
1684	[1,3,4,5] PAVLOPO... 78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1693±2	[1] CHIBA 91	CNTR		$\overline{p}d \to \gamma X$
1694±2.0	[1,2,3,4] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1713.0±2.6	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1731.0±1.5	[1] CHIBA 87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1771±1.0	[1,3,4,7] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE	DOCUMENT ID	TECN	COMMENT
1812.3±1.2	CHIBA 97	CNTR	$\overline{p}d \to nX$
3.7±1.3	CHIBA 97	CNTR	$\overline{p}d \to nX$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1856.6±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
20 ±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 1870	[8] DALKAROV 97	RVUE	–	0.0 $\overline{p}d \to p3\pi^-2\pi^+$
~ 10	[8] DALKAROV 97	RVUE	–	0.0 $\overline{p}d \to p3\pi^-2\pi^+$
1873±2.5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
< 5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1897±17	[9] ABASHIAN 76	STRC	8 $\pi^-p \to p3\pi$
110±82	[9] ABASHIAN 76	STRC	8 $\pi^-p \to p3\pi$
1897± 1	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold
25± 6	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 1920	[10] EVANGELISTA 79	OMEG	10,16 $\pi^-p \to \overline{p}p$
~ 190	EVANGELISTA 79	OMEG	10,16 $\pi^-p \to \overline{p}p$

Meson Particle Listings

$\overline{N}N(1100\text{–}3600)$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$1937.3^{+1.3}_{-0.7}$		[11] FRANKLIN	87	SPEC		0.586 $\overline{p}p$
< 3.0		[11] FRANKLIN	87	SPEC		0.586 $\overline{p}p$
1930 ± 2		[12] ASTON	80D	OMEG		$\gamma p \rightarrow p\overline{p}X$
12 ± 7		[12] ASTON	80D	OMEG		$\gamma p \rightarrow p\overline{p}X$
1940 ± 1	36	DAUM	80E	CNTR	0	93 $pp \rightarrow \overline{p}pX$
~ 6.0		DAUM	80E	CNTR		93 $pp \rightarrow \overline{p}pX$
1949 ± 10		[13] DEFOIX	80	HBC	0	$\overline{p}p \rightarrow 5\pi$
80 ± 20		[13] DEFOIX	80	HBC	0	$\overline{p}p \rightarrow 5\pi$
1939 ± 2		[14] HAMILTON	80B	CNTR	0	S channel $\overline{p}p$
22 ± 6		[14] HAMILTON	80B	CNTR	0	S channel $\overline{p}p$
1935.5 ± 1.0		SAKAMOTO	79	HBC	0	0.37–0.73 $\overline{p}p$
2.8 ± 1.4		SAKAMOTO	79	HBC	0	0.37–0.73 $\overline{p}p$
1939 ± 3		BRUCKNER	77	SPEC	0	0.4–0.85 $\overline{p}p$
< 4.0		BRUCKNER	77	SPEC	0	0.4–0.85 $\overline{p}p$
1935.9 ± 1.0		[15] CHALOUPKA	76	HBC	0	$\overline{p}p$ total,elastic
$8.8^{+4.3}_{-3.2}$		[16] CHALOUPKA	76	HBC	0	$\overline{p}p$ total,elastic
1942 ± 5		[17] D'ANDLAU	75	HBC	0	0.175–0.750 $\overline{p}p$
57.5 ± 5		[18] D'ANDLAU	75	HBC	0	0.175–0.750 $\overline{p}p$
$1934.4^{+2.6}_{-1.4}$		[19] KALOGERO...	75	DBC	$-$	$\overline{p}N$ annihilation
11^{+11}_{-4}		[20] KALOGERO...	75	DBC	$-$	$\overline{p}N$ annihilation
1932 ± 2		[15] CARROLL	74	CNTR		S channel $\overline{p}p \rightarrow d$
9^{+4}_{-3}		[16] CARROLL	74	CNTR		S channel $\overline{p}p \rightarrow d$
1968		[21] BENVENUTI	71	HBC	0	0.1–0.8 $\overline{p}p$
35		[21] BENVENUTI	71	HBC	0	0.1–0.8 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1949 ± 10	[22] DEFOIX	80	HBC	0	0.0–1.2 $\overline{p}p \rightarrow 5\pi$
80 ± 20	[22] DEFOIX	80	HBC	0	0.0–1.2 $\overline{p}p \rightarrow 5\pi$

VALUE (MeV)	DOCUMENT ID		COMMENT
2011 ± 7	[23] FERRER	93	$\pi^- p \rightarrow pp\overline{p}\pi^-\pi^0$
25^{+10}_{-25}	[23] FERRER	93	$\pi^- p \rightarrow pp\overline{p}\pi^-\pi^0$
2025	GIBBARD	79	$e^- p \rightarrow e^- pp\overline{p}$
< 30	GIBBARD	79	$e^- p \rightarrow e^- pp\overline{p}$
2020 ± 3	BENKHEIRI	77	$\pi^- p \rightarrow pp\overline{p}\pi^-$
24 ± 12	BENKHEIRI	77	$\pi^- p \rightarrow pp\overline{p}\pi^-$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2022 ± 6	[24] AZOOZ	83	HYBR	+	6 $\overline{p}p \rightarrow p\overline{n}3\pi$
14 ± 13	[24] AZOOZ	83	HYBR	+	6 $\overline{p}p \rightarrow p\overline{n}3\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2023 ± 5	BODENKAMP	83	SPEC	0	$\gamma p \rightarrow \overline{p}pp$
27 ± 12	BODENKAMP	83	SPEC	0	$\gamma p \rightarrow \overline{p}pp$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2026 ± 5	[24] AZOOZ	83	HYBR	$-$	4 $\overline{p}p \rightarrow \overline{p}n3\pi$
20 ± 11	[24] AZOOZ	83	HYBR	$-$	4 $\overline{p}p \rightarrow \overline{p}n3\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2080 ± 10	[25] KREYMER	80	STRC	0	13 $\pi^- d \rightarrow p\overline{p}n(n)$
110 ± 20	[25] KREYMER	80	STRC	0	13 $\pi^- d \rightarrow p\overline{p}n(n)$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090 ± 20	[26] KREYMER	80	STRC	13 $\pi^- d \rightarrow np\overline{p}\pi^- p$
170 ± 50	[26] KREYMER	80	STRC	13 $\pi^- d \rightarrow np\overline{p}\pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2110	[27] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$
~ 330	[27] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2110 ± 10	[28] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
190 ± 10	[28] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2141	[29] DONALD	73	HBC	0	$\overline{p}p$ S channel
14	[29] DONALD	73	HBC	0	$\overline{p}p$ S channel

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2180 ± 10	[30] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
270 ± 10	[30] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2207 ± 13	[31] ALLES-...	67B	HBC	0	5.7 $\overline{p}p$
62 ± 52	[31] ALLES-...	67B	HBC	0	5.7 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2210^{+79}_{-21}	EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+ K^- n$
~ 203	EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+ K^- n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2231.9 ± 0.1	[32] BARNES	94	SPEC	0–46 $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$
0.59 ± 0.25	[32] BARNES	94	SPEC	0–46 $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$
~ 2229.2	CARBONELL	93	RVUE	$\overline{p}p \rightarrow \Lambda\overline{\Lambda}$
~ 1.8	CARBONELL	93	RVUE	$\overline{p}p \rightarrow \Lambda\overline{\Lambda}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2260	[33] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$
~ 440	[33] EVANGELISTA	79	OMEG	10,16 $\pi^- p \rightarrow \overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2307 ± 6	ALPER	80	CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$
245 ± 20	ALPER	80	CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2380 ± 10	[34] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
380 ± 20	[34] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2450 ± 10	[35] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
280 ± 20	[35] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2480 ± 30	[36] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$
210 ± 25	[36] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
~ 2500	[37] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^- K^+$
~ 150	[37] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^- K^+$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2710 ± 20	ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$
170 ± 40	ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p}n$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2850 ± 5	[38] BRAUN	76	DBC	$-$	5.5 $\overline{p}d \rightarrow N\overline{N}\pi$
< 39	[38] BRAUN	76	DBC	$-$	5.5 $\overline{p}d \rightarrow N\overline{N}\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3370 ± 10	[39] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$
150 ± 40	[39] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3600 ± 20	[39] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$
140 ± 20	[39] ALEXANDER	72	HBC	0	6.94 $\overline{p}p$

[1] Not seen by GRAF 91.

[2] Not seen by CHIBA 88, ANGELOPOULOS 86, ADIELS 86.

[3] They looked for radiative transitions to bound $p\overline{p}$ states, mono-energetic γ rays detected.

[4] Observed widths consistent with experimental resolution.

[5] Not seen by ADIELS 86.

[6] From analysis of difference of π^- and π^+ spectra.

[7] Not seen by CHIBA 88, ANGELOPOULOS 86.

[8] From a phenomenological analysis of ASTERIX data.

[9] Produced backwards.

[10] $I(J^P) = 1(1^-)$ from a mass dependent partial-wave analysis taking solution A.

[11] From reanalysis of data from JASTRZEMBSKI 81.

[12] Not seen by BUSENITZ 89.

[13] From energy dependence of 5π cross section. $I^G = 1^-$ from observation of $\omega\rho$ decay. $P = +$ and $J > 1$. $a_2(1320)\pi\pi$ also seen.

[14] $I = 0$ favored, $J = 0$ or 1, seen in total $\overline{p}p$ total cross section. Primarily from annihilation reactions. Not seen in $\overline{p}d$ total and annihilation cross sections.

[15] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77.

[16] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77. Not seen by CLOUGH 84.

[17] From energy dependence of far backward elastic scattering. Some indication of additional structure.

[18] From energy dependence of far backward elastic scattering. Some indication of additional structure.

[19] Not seen by ALBERI 79 with comparable statistics.

[20] Not seen by ALBERI 79 with comparable statistics.

[21] Seen as a bump in the $\overline{p}p \rightarrow K^0_S K^0_L$ cross section with $J^{PC} = 1^{--}$.

[22] Isospin 1 favored.

[23] Not seen by AJALTOUNI 82, ARMSTRONG 79, BUZZO 97.

[24] Not seen by BIONTA 80, CARROLL 80, HAMILTON 80, BANKS 81, CHUNG 81, BARNETT 83.

[25] Neutron spectator. See also $np\overline{p}\pi^-(p)$ channel following.

[26] Proton spectator. See also $p\overline{p}n(n)$ channel above.
[27] $I(J^P) = 1(3^-)$ from a mass dependent partial-wave analysis taking solution A.
[28] $I(J^P) = 1(3^-)$ from amplitude analysis assuming one-pion exchange.
[29] Seen in final state $\omega\pi^+\pi^-$.
[30] $I(J^P) = 0(2^+)$ from amplitude analysis assuming one-pion exchange.
[31] ALLES-BORELLI 67B see neutral mode only $\pi^+\pi^-\pi^0$.
[32] Supersedes CARBONELL 93.
[33] $I(J^P) = 0(4^+)$ from a mass dependent partial-wave analysis taking solution A.
[34] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[35] $I(J^P) = 1(5^-)$ from amplitude analysis assuming one-pion exchange.
[36] $I(J^P) = 1(5^-)$ from amplitude analysis of $\overline{p}p \rightarrow \pi\pi$.
[37] I=0,1 $J^P = 5^-$ from Barrelet-zero analysis.
[38] Decays to $\overline{N}N$ and $\overline{N}N\pi$. Not seen by BARNETT 83.
[39] Decays to $4\pi^+4\pi^-$.

$\overline{N}N$(1100–3600) REFERENCES

BUZZO	97	ZPHY C76 475	A. Buzzo, Drijard+	(JETSET Collab.)
CHIBA	97	PR D55 40	+Doi, Fujitani+	(FUKI, INUS, KEK, SANG, OSAK, TMU)
DALKAROV	97	PL B392 229	+Kolybasov, Shapiro+	(LEBD)
BARNES	94	PL B331 203	+Birien+	(PS185 Collab.)
CARBONELL	93	PL B306 407	+Protasov, Dalkarov	(ISNG, LEBD)
FERRER	93	NP A558 191c	+Grigonian	(WA56 Collab.)
CHIBA	91	PR D44 1933	+Fujitani+	(FUKI, KEK, SANG, OSAK, TMU)
GRAF	91	PR D44 1945	+Fero, Gee+	(UCI, PENN, NMSU, KARLK, KARLE, ATHU)
BUSENITZ	89	PR D40 1	+Olszewski, Callahan+	(ILL, FNAL)
CHIBA	88	PL B202 447	+Doi	(FUKI, INUS, KEK, SANG, OSAK, TMU)
CHIBA	87	PR D36 3321	+Doi+	(FUKI, INUS, KEK, SANG, OSAK, TMU)
DAFTARI	87	PRL 58 859	+Gray, Kalogeropoulos, Roy	(SYRA)
FRANKLIN	87	PL B184 81		
ADIELS	86	PL B182 405	+Backenstoss+	(STOH, BASL, LASL, THES, CERN)
ANGELOPO...	86	PL B178 441	Angelopoulos+	(ATHU, UCI, KARLK, KARLE, NMSU, PENN)
BRIDGES	86B	PRL 56 215	+Daftari, Kalogeropoulos, Debbe+	(SYRA, CASE)
BRIDGES	86D	PL B180 313	+Brown, Daftari+	(SYRA, BNL, CASE, UMD, COLU)
ADIELS	84	PL 138B 235	+	(BASL, KARLK, KARLE, STOH, STRB, THES)
CLOUGH	84	PL 146B 299	+Beard, Bugg+	(SURR, LOQM, ANIK, TRST, GEVA)
AZOOZ	83	PL 122B 471	+Butterworth	(LOIC, RHEL, SACL, SLAC, TOHOK+)
BARNETT	83	PR D27 493	+Blockus, Burka, Chien, Christian+	(JHU)
BODENKAMP	83	PL 133B 275	+Fries, Behrend, Fenner+	(KARLK, KARLE, DESY)
RICHTER	83	PL 126B 284	+Adiels	(BASL, KARLK, KARLE, STOH, STRB, THES)
AJALTOUNI	82	NP B209 301	+Bachman+	(CERN, NEUC+)
BANKS	81	PL 100B 191	+Booth, Campbell, Armstrong+	(LIVP, CERN)
CHUNG	81	PRL 46 395	+Bensinger+	(BNL, BRAN, CINC, FSU, MASD)
JASTRZEM...	81	PR D23 2784	Jastrzembski, Mandelkern+	(TEMP, UCI, UNM)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ASTON	80D	PL 93B 517		(BONN, CERN, EPOL, GLAS, LANC, MCHS, ORSAY+)
BIONTA	80	PRL 44 909	+Carroll, Edelstein+	(BNL, CMU, FNAL, MASD)
CARROLL	80	PRL 44 1572	+Chiang, Johnson, Cester, Webb+	(BNL, PRIN)
DAUM	80E	PL 90B 475	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
DEFOIX	80	NP B162 12	+Dobrzynski, Angelini, Bigi+	(CDEF, PISA)
HAMILTON	80	PRL 44 1179	+Pun, Tripp, Lazarus+	(LBL, BNL, MTHO)
HAMILTON	80B	PRL 44 1182	+Pun, Tripp, Lazarus+	(LBL, BNL, MTHO)
KREYMER	80	PR D22 36	+Baggett, Fieguth+	(IND, PURD, SLAC, VAND)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
ALBERI	79	PL 83B 247	+Alvear, Castelli, Poropat+	(TRST, CERN, IFRJ)
ARMSTRONG	79	PL B85 304	+Baccari, Belletti, Booth+	(DESY, GLAS)
EVANGELISTA	79	NP B153 253	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
GIBBARD	79	PRL 42 1593	+Ahrens, Berkelman, Cassel, Day, Harding+	(CORN)
SAKAMOTO	79	NP B158 410	+Hashimoto, Sai, Yamamoto+	(INUS)
CARTER	78B	NP B141 467		(LOQM)
PAVLOPO...	78	PL 72B 415	Pavlopoulos+	(KARLK, KARLE, BASL, CERN, STOH, STRB)
BENKHEIRI	77	PL 68B 483	+Boucrot+	(CERN, CDEF, EPOL, LALO)
BRUCKNER	77	PL 67B 222	+Granz, Ingham, Kilian+	(MPIH, HEIDP, CERN)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
ABASHIAN	76	PR D13 5	+Watson, Gelfand, Buttram+	(ILL, ANL, CHIC, ISU)
BRAUN	76	PL 60B 481	+Brick, Fridman, Gerber, Juillot, Maurer+	(STRB)
CHALOUPKA	76	PL 61B 487	+	(CERN, LIVP, MONS, PADO, ROMA, TRST)
ALSTON-...	75	PRL 35 1685	Alston-Garnjost, Kenney, Pollard, Ross, Tripp+	(LBL, MTHO)
D'ANDLAU	75	PL 58B 223	+Cohen-Ganouna, Laloum, Lutz, Petri	(CDEF, PISA)
KALOGERO...	75	PRL 34 1047	Kalogeropoulos, Tzanakos	(SYRA)
CARROLL	74	PRL 32 247	+Chiang, Kycia, Li, Mazur, Michael+	(BNL)
DONALD	73	NP B61 333	+Edwards, Gibbins, Briand, Duboc+	(LIVP, PARIS)
ALEXANDER	72	NP B45 29	+Bar-Nir, Benary, Dagan+	(TELA)
BENVENUTI	71	PRL 27 283	+Cline, Rutz, Reeder, Scherer	(WISC)
ALLES-...	67B	NC 50A 776	Alles-Borelli, French, Frisk+	(CERN, BONN) G
BETTINI	66	NC 42A 695	+Cresti, Limentani, Bertanza, Bigi+	(PADO, PISA)

OTHER RELATED PAPERS

BUZZO	97	ZPHY C76 475	A. Buzzo, Drijard+	(JETSET Collab.)
TANIMORI	90	PR D41 744	+Ishimoto+	(KEK, INUS, KYOT, TOHOK, HIRO)
LIU	87	PRL 58 2288	+Kiu, Li	(STON)
ARMSTRONG	86C	PL B175 383	+Chu, Clement, Elinon+	(BNL, HOUS, PENN, RICE)
BRIDGES	86	PRL 56 211	+Brown+	(BLSU, BNL, CASE, COLU, UMD, SYRA)
BRIDGES	86C	PRL 57 1534	+Daftari, Kalogeropoulos+	(SYRA) JP
DOVER	86	PRL 57 1207	+	(BNL) JP
ANGELOPO...	85	PL 159B 210	Angelopoulos+	(ATHU, UCI, UNM, PENN, TEMP)
BODENKAMP	85	NP B255 717	+Fries, Behrend, Hesse+	(KARLK, KARLE, DESY)
AZOOZ	84	NP B244 277	+Butterworth	(LOIC, RHEL, SACL, SLAC, TOHOK+)

X(1900–3600)

OMITTED FROM SUMMARY TABLE

THE X(1900–3600) REGION

This high-mass region is covered nearly continuously with evidence for peaks of various widths and decay modes. As no satisfactory grouping into particles is yet possible, we list together in order of increasing mass all the $Y=0$ bumps above 1900 MeV that are coupled neither to $\overline{N}N$ nor to e^+e^-.

X(1900–3600) MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	*DOCUMENT ID*
1900 to 3600 OUR LIMIT	

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1870±40	[1] ALDE	86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$
250±30	[1] ALDE	86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1898±18	100	THOMPSON	74	HBC	+	13 $\pi^+ p \rightarrow 2\rho X$
108^{+41}_{-27}	100	THOMPSON	74	HBC	+	13 $\pi^+ p \rightarrow 2\rho X$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1900± 40	100	BOESEBECK	68	HBC	+	8 $\pi^+ p \rightarrow \pi^+\pi^0 X$
216±105	100	BOESEBECK	68	HBC	+	8 $\pi^+ p \rightarrow \pi^+\pi^0 X$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1929±14	[2] FOCACCI	66	MMS	−	3–12 $\pi^- p$
22± 2	[2] FOCACCI	66	MMS	−	3–12 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1970±10	CHLIAPNIK...	80	HBC	0	32 $K^+ p \rightarrow 2K^0_S 2\pi X$
40±20	CHLIAPNIK...	80	HBC	0	32 $K^+ p \rightarrow 2K^0_S 2\pi X$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1973±15	30	CASO	70	HBC	−	11.2 $\pi^- p \rightarrow \rho 2\pi$
80	30	CASO	70	HBC	−	11.2 $\pi^- p \rightarrow \rho 2\pi$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2070	50	TAKAHASHI	72	HBC	8 $\pi^- p \rightarrow N 2\pi$
160	50	TAKAHASHI	72	HBC	8 $\pi^- p \rightarrow N 2\pi$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
~ 2104		BUGG	95	MRK3		$J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$
2103±50	586	[3] BISELLO	89B	DM2		$J/\psi \rightarrow 4\pi\gamma$
187±75	586	[3] BISELLO	89B	DM2		$J/\psi \rightarrow 4\pi\gamma$
2100±40		[4] ALDE	86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$
250±40		[4] ALDE	86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2141±12	389	GREEN	86	MPSF	400 $pA \rightarrow 4KX$
49±28	389	GREEN	86	MPSF	400 $pA \rightarrow 4KX$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2190±10	CLAYTON	67	HBC	±	2.5 $\overline{p}p \rightarrow a_2, \omega$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2195±15	[2] FOCACCI	66	MMS	–	3–12 $\pi^- p$
39±14	[2] FOCACCI	66	MMS	–	3–12 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2207±22	[5] CASO	70	HBC	–	11.2 $\pi^- p$
130	[5] CASO	70	HBC	–	11.2 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2280± 50	ATKINSON	85	OMEG	20–70 $\gamma p \rightarrow p \omega \pi^+ \pi^- \pi^0$
440±110	ATKINSON	85	OMEG	20–70 $\gamma p \rightarrow p \omega \pi^+ \pi^- \pi^0$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2300±100	ATKINSON	84F	OMEG	±0	20–70 $\gamma p \rightarrow \rho f$
~ 250	ATKINSON	84F	OMEG	±0	20–70 $\gamma p \rightarrow \rho f$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2330±30	ATKINSON	88	OMEG	0	25–50 $\gamma p \rightarrow \rho^\pm \rho^0 \pi^\mp$
435±75	ATKINSON	88	OMEG	0	25–50 $\gamma p \rightarrow \rho^\pm \rho^0 \pi^\mp$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2340±20	126	[6] BALTAY	75	HBC	+	15 $\pi^+ p \rightarrow p 5\pi$
180±60	126	[6] BALTAY	75	HBC	+	15 $\pi^+ p \rightarrow p 5\pi$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2382±24	[2] FOCACCI	66	MMS	–	3–12 $\pi^- p$
62± 6	[2] FOCACCI	66	MMS	–	3–12 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2500±32	ANDERSON	69	MMS	–	16 $\pi^- p$ backward
87	ANDERSON	69	MMS	–	16 $\pi^- p$ backward

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2620±20	550	BAUD	69	MMS	–	8–10 $\pi^- p$
85±30	550	BAUD	69	MMS	–	8–10 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2676±27	[5] CASO	70	HBC	–	11.2 $\pi^- p$
150	[5] CASO	70	HBC	–	11.2 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2747±32	DENNEY	83	LASS	10 $\pi^+ N$
195±75	DENNEY	83	LASS	10 $\pi^+ N$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2800±20	640	BAUD	69	MMS	–	8–10 $\pi^- p$
46±10	640	BAUD	69	MMS	–	8–10 $\pi^- p$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2820±10	15	[7] SABAU	71	HBC	+	8 $\pi^+ p$
50±10	15	[7] SABAU	71	HBC	+	8 $\pi^+ p$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2880±20	230	BAUD	69	MMS	–	8–10 $\pi^- p$
< 15	230	BAUD	69	MMS	–	8–10 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3025±20	BAUD	70	MMS	–	10.5–13 $\pi^- p$
~ 25	BAUD	70	MMS	–	10.5–13 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3075±20	BAUD	70	MMS	–	10.5–13 $\pi^- p$
~ 25	BAUD	70	MMS	–	10.5–13 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3145±20	BAUD	70	MMS	–	10.5–15 $\pi^- p$
< 10	BAUD	70	MMS	–	10.5–15 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3475±20	BAUD	70	MMS	–	14–15.5 $\pi^- p$
~ 30	BAUD	70	MMS	–	14–15.5 $\pi^- p$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3535±20	BAUD	70	MMS	–	14–15.5 $\pi^- p$
~ 30	BAUD	70	MMS	–	14–15.5 $\pi^- p$

[1] Seen in $J = 2$ wave in one of the two ambiguous solutions.

[2] Not seen by ANTIPOV 72, who performed a similar experiment at 25 and 40 GeV/c.

[3] ASTON 81B sees no peak, has 850 events in Ajinenko+Barth bins. ARESTOV 80 sees no peak.

[4] Seen in $J = 0$ wave in one of the two ambiguous solutions.

[5] Seen in $\rho^- \pi^+ \pi^-$ (ω and η antiselected in 4π system).

[6] Dominant decay into $\rho^0 \rho^0 \pi^+$. BALTAY 78 finds confirmation in $2\pi^+ \pi^- 2\pi^0$ events which contain $\rho^+ \rho^0 \pi^0$ and $2\rho^+ \pi^-$.

[7] Seen in $(K \overline{K} \pi \pi)$ mass distribution.

$X(1900\text{–}3600)$ REFERENCES

BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
ATKINSON	88	ZPHY C38 535	+Axon+	(BONN, CERN, GLAS, LANC, MCHS, CURIN)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
ATKINSON	84F	NP B239 1	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
ASTON	81B	NP B189 205	+	(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
ARESTOV	80	IHEP 80-165	+Bogoljubski+	(SERP)
CHLIAPNIK...	80	ZPHY C3 285	Chliapnikov, Gerdyukov+	(SERP, BRUX, MONS)
BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
BALTAY	75	PRL 35 891	+Cautis, Cohen, Kalelkar, Pisello+	(COLU, BING)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHOK, PENN, NDAM, ANL)
SABAU	71	LNC 1 514	+Uretsky	(BUCH, ANL)
BAUD	70	PL 31B 549	+Benz+	(CERN Boson Spectrometer Collab.)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
BAUD	69	PL 30B 129	+Benz+	(CERN Boson Spectrometer Collab.)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CLAYTON	67	Heidelberg Conf. 57	+Mason, Muirhead, Filippas+	(LIVP, ATHU)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)

OTHER RELATED PAPERS

ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
CHIKOVANI	66	PL 22 233	+Kienzle, Maglich+	(SERP)

STRANGE MESONS
$(S = \pm1,\ C = B = 0)$

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\overline{K}^0 = \bar{d}s$, $K^- = \bar{u}s$, similarly for K^*'s

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

THE CHARGED KAON MASS

Revised 1994 by T.G. Trippe, (LBNL).

The average of the six charged kaon mass measurements which we use in the Particle Listings is

$$m_{K^\pm} = 493.677 \pm 0.013 \text{ MeV (S = 2.4)} , \qquad (1)$$

where the error has been increased by the scale factor S. The large scale factor indicates a serious disagreement between different input data. The average before scaling the error is

$$m_{K^\pm} = 493.677 \pm 0.005 \text{ MeV} ,$$
$$\chi^2 = 22.9 \text{ for 5 D.F., Prob. } = 0.04\% , \qquad (2)$$

where the high χ^2 and correspondingly low χ^2 probability further quantify the disagreement.

The main disagreement is between the two most recent and precise results,

$$m_{K^\pm} = 493.696 \pm 0.007 \text{ MeV} \qquad \text{DENISOV 91}$$
$$m_{K^\pm} = 493.636 \pm 0.011 \text{ MeV (S = 1.5)} \quad \text{GALL 88}$$
$$\text{Average} = 493.679 \pm 0.006 \text{ MeV}$$
$$\chi^2 = 21.2 \text{ for 1 D.F., Prob. } = 0.0004\% , \qquad (3)$$

both of which are measurements of x-ray energies from kaonic atoms. Comparing the average in Eq. (3) with the overall average in Eq. (2), it is clear that DENISOV 91 and GALL 88 dominate the overall average, and that their disagreement is responsible for most of the high χ^2.

The GALL 88 measurement was made using four different kaonic atom transitions, K^- Pb (9 → 8), K^- Pb (11 → 10), K^- W (9 → 8), and K^- W (11 → 10). The $m_{K^\pm}$ values they obtain from each of these transitions is shown in the Particle Listings and in Fig. 1Their K^- Pb (9 → 8) $m_{K^\pm}$is below and somewhat inconsistent with their other three transitions. The average of their four measurements is

$$m_{K^\pm} = 493.636 \pm 0.007 ,$$
$$\chi^2 = 7.0 \text{ for 3 D.F., Prob. } = 7.2\% . \qquad (4)$$

This is a low but acceptable χ^2 probability so, to be conservative, GALL 88 scaled up the error on their average by S=1.5 to obtain their published error ±0.011 shown in Eq. (3) above and used in the Particle Listings average.

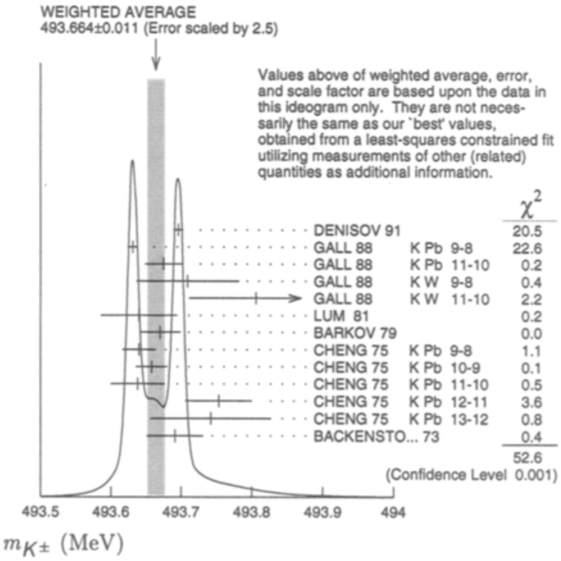


Figure 1: Ideogram of $m_{K^\pm}$ mass measurements. GALL 88 and CHENG 75 measurements are shown separately for each transition they measured.

The ideogram in Fig. 1 shows that the DENISOV 91 measurement and the GALL 88 K^- Pb (9 → 8) measurement yield two well-separated peaks. One might suspect the GALL 88 K^- Pb (9 → 8) measurement since it is responsible both for the internal inconsistency in the GALL 88 measurements and the disagreement with DENISOV 91.

To see if the disagreement could result from a systematic problem with the K^- Pb (9 → 8) transition, we have separated the CHENG 75 data, which also used K^- Pb, into its separate transitions. Fig. 1shows that the CHENG 75 and GALL 88 K^- Pb (9 → 8) values are consistent, suggesting the possibility of a common effect such as contaminant nuclear γ rays near the K^- Pb (9 → 8) transition energy, although the CHENG 75 errors are too large to make a strong conclusion. The average of all 13 measurements has a χ^2 of 52.6 as shown in Fig. 1and the first line of Table 1, yielding an unacceptable χ^2 probability of 0.00005%. The second line of Table 1 excludes both the GALL 88 and CHENG 75 measurements of the K^- Pb (9 → 8) transition and yields a χ^2 probability of 43%. The third [fourth] line of Table 1 excludes only the GALL 88 K^- Pb (9 → 8) [DENISOV 91] measurement and yields a χ^2 probability of 20% [8.6%]. Table 1 shows that removing both measurements of the K^- Pb (9 → 8) transition produces the most consistent set of data, but that excluding only the GALL 88 K^- Pb (9 → 8) transition or DENISOV 91 also produces acceptable probabilities.

Yu.M. Ivanov, representing DENISOV 91, has estimated corrections needed for the older experiments because of improved ^{192}Ir and ^{198}Au calibration γ-ray energies. He estimates

Table 1: $m_{K^{\pm}}$ averages for some combinations of Fig. 1data.

$m_{K^{\pm}}$ (MeV)	χ^2	D.F.	Prob. (%)	Measurements used
493.664 ± 0.004	52.6	12	0.00005	all 13 measurements
493.690 ± 0.006	10.1	10	43	no K^- Pb(9→8)
493.687 ± 0.006	14.6	11	20	no GALL 88 K^- Pb(9→8)
493.642 ± 0.006	17.8	11	8.6	no DENISOV 91

that CHENG 75 and BACKENSTOSS 73 $m_{K^{\pm}}$ values could be raised by about 15 keV and 22 keV, respectively. With these estimated corrections, Table 1 becomes Table 2. The last line of Table 2 shows that if such corrections are assumed, then GALL 88 K^- Pb (9 → 8) is inconsistent with the rest of the data even when DENISOV 91 is excluded. Yu.M. Ivanov warns that these are rough estimates. Accordingly, we do not use Table 2 to reject the GALL 88 K^- Pb (9 → 8) transition, but we note that a future reanalysis of the CHENG 75 data could be useful because it might provide supporting evidence for such a rejection.

Table 2: $m_{K^{\pm}}$ averages for some combinations of Fig. 1data after raising CHENG 75 and BACKENSTOSS 73 values by 0.015 and 0.022 MeV respectively.

$m_{K^{\pm}}$ (MeV)	χ^2	D.F.	Prob. (%)	Measurements used
493.666 ± 0.004	53.9	12	0.00003	all 13 measurements
493.693 ± 0.006	9.0	10	53	no K^- Pb(9→8)
493.690 ± 0.006	11.5	11	40	no GALL 88 K^- Pb(9→8)
493.645 ± 0.006	23.0	11	1.8	no DENISOV 91

The GALL 88 measurement uses a Ge semiconductor spectrometer which has a resolution of about 1 keV, so they run the risk of some contaminant nuclear γ rays. Studies of γ rays following stopped π^- and Σ^- absorption in nuclei (unpublished) do not show any evidence for contaminants according to GALL 88 spokesperson, B.L. Roberts. The DENISOV 91 measurement uses a crystal diffraction spectrometer with a resolution of 6.3 eV for radiation at 22.1 keV to measure the 4f-3d transition in K^- ^{12}C. The high resolution and the light nucleus reduce the probability for overlap by contaminant γ rays, compared with the measurement of GALL 88. The DENISOV 91 measurement is supported by their high-precision measurement of the 4d-2p transition energy in π^- ^{12}C, which is good agreement with the calculated energy.

While we suspect that the GALL 88 K^- Pb (9 → 8) measurements could be the problem, we are unable to find clear grounds for rejecting it. Therefore, we retain their measurement in the average and accept the large scale factor until further information can be obtained from new measurements and/or from reanalysis of GALL 88 and CHENG 75 data.

We thank B.L. Roberts (Boston Univ.) and Yu.M. Ivanov (Petersburg Nuclear Physics Inst.) for their extensive help in understanding this problem.

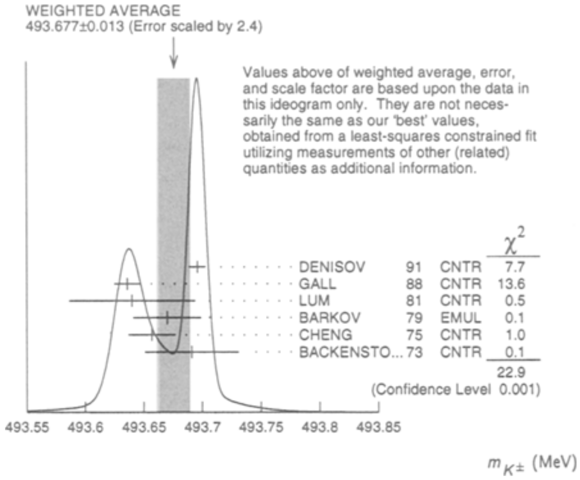
$K^{\pm}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.				
493.677±0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.				
493.696±0.007	[1] DENISOV	91	CNTR	−	Kaonic atoms
493.636±0.011	[2] GALL	88	CNTR	−	Kaonic atoms
493.640±0.054	LUM	81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+ e^- \rightarrow K^+ K^-$
493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
493.631±0.007	GALL	88	CNTR	−	K^- Pb (9→ 8)
493.675±0.026	GALL	88	CNTR	−	K^- Pb (11→ 10)
493.709±0.073	GALL	88	CNTR	−	K^- W (9→ 8)
493.806±0.095	GALL	88	CNTR	−	K^- W (11→ 10)
493.640±0.022±0.008	[3] CHENG	75	CNTR	−	K^- Pb (9→ 8)
493.658±0.019±0.012	[3] CHENG	75	CNTR	−	K^- Pb (10→ 9)
493.638±0.035±0.016	[3] CHENG	75	CNTR	−	K^- Pb (11→ 10)
493.753±0.042±0.021	[3] CHENG	75	CNTR	−	K^- Pb (12→ 11)
493.742±0.081±0.027	[3] CHENG	75	CNTR	−	K^- Pb (13→ 12)
493.662±0.19	KUNSELMAN	74	CNTR	−	Kaonic atoms
493.78 ±0.17	GREINER	65	EMUL	+	
493.7 ±0.3	BARKAS	63	EMUL	−	
493.9 ±0.2	COHEN	57	RVUE	+	

[1] Error increased from 0.0059 based on the error analysis in IVANOV 92.

[2] This value is the authors' combination of all of the separate transitions listed for this paper.

[3] The CHENG 75 values for separate transitions were calculated from their Table 7 transition energies. The first error includes a 20% systematic error in the noncircular contaminant shift. The second error is due to a ±5 eV uncertainty in the theoretical transition energies.



$m_{K^+} - m_{K^-}$

Test of *CPT*.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
−0.032±0.090	1.5M	[4] FORD	72	ASPK	±

[4] FORD 72 uses $m_{\pi^+} - m_{\pi^-} = +28 \pm 70$ keV.

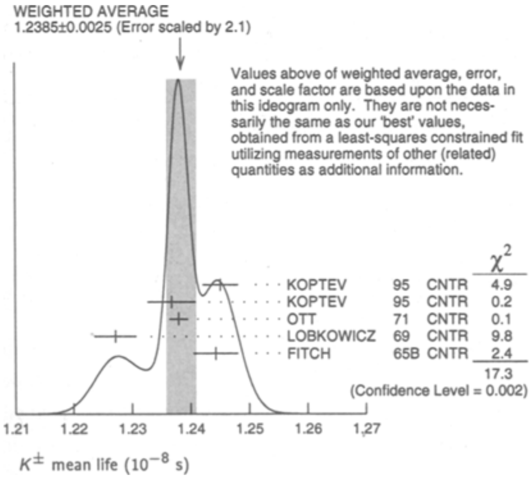
$K^{\pm}$ MEAN LIFE

VALUE (10^{-8} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.2386±0.0024 OUR FIT	Error includes scale factor of 2.0.					
1.2385±0.0025 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.					
1.2451±0.0030	250k	KOPTEV	95	CNTR		*K* at rest, U target
1.2368±0.0041	150k	KOPTEV	95	CNTR		*K* at rest, Cu target
1.2380±0.0016	3M	OTT	71	CNTR	+	*K* at rest
1.2272±0.0036		LOBKOWICZ	69	CNTR	+	*K* in flight
1.2443±0.0038		FITCH	65B	CNTR	+	*K* at rest

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.2415 ± 0.0024	400k	[5] KOPTEV	95	CNTR		K at rest
1.221 ± 0.011		FORD	67	CNTR	$\pm$	
1.231 ± 0.011		BOYARSKI	62	CNTR	$+$	
$1.25 \ {}^{+0.22}_{-0.17}$		BARKAS	61	EMUL		
$1.27 \ {}^{+0.36}_{-0.23}$	51	BHOWMIK	61	EMUL		
1.31 ± 0.08	293	NORDIN	61	HBC	$-$	
1.24 ± 0.07		NORDIN	61	RVUE	$-$	
1.38 ± 0.24	33	FREDEN	60B	EMUL		
1.21 ± 0.06		BURROWES	59	CNTR		
1.60 ± 0.3	52	EISENBERG	58	EMUL		
$0.95 \ {}^{+0.36}_{-0.25}$		ILOFF	56	EMUL		

[5] KOPTEV 95 report this weighted average of their U-target and Cu-target results, where they have weighted by $1/\sigma$ rather than $1/\sigma^2$.



$(\tau_{K^+} - \tau_{K^-}) / \tau_{\text{average}}$

This quantity is a measure of *CPT* invariance in weak interactions.

VALUE (%)	*DOCUMENT ID*		*TECN*
0.11 ±0.09 OUR AVERAGE	Error includes scale factor of 1.2.		
0.090 ± 0.078	LOBKOWICZ	69	CNTR
0.47 ± 0.30	FORD	67	CNTR

RARE KAON DECAYS

Revised November 1997 by L. Littenberg (BNL) and G. Valencia (Iowa State University)

A. Introduction: There are several useful reviews on rare kaon decays and related topics [1–10]. The current activity in rare kaon decays can be divided roughly into four categories:

1. Searches for explicit violations of the Standard Model
2. Measurements of Standard Model parameters
3. Searches for *CP* violation
4. Studies of strong interactions at low energy.

The paradigm of Category 1 is the lepton flavor violating decay $K_L \to \mu e$. Category 2 includes processes such as $K^+ \to \pi^+ \nu\overline{\nu}$, which is sensitive to $|V_{td}|$. Much of the interest in Category 3 is focussed on the decays $K_L \to \pi^0 \ell\overline{\ell}$, where $\ell \equiv e, \mu, \nu$. Category 4 includes reactions like $K^+ \to \pi^+ \ell^+ \ell^-$ which constitute a testing ground for the ideas of chiral perturbation theory. Other reactions of this type are $K_L \to \pi^0 \gamma\gamma$, which also scales a *CP*-conserving background to *CP* violation in $K_L \to \pi^0 \ell^+ \ell^-$ and $K_L \to \gamma \ell^+ \ell^-$, which could possibly shed light on long distance contributions to $K_L \to \mu^+ \mu^-$.

B. Explicit violations of the Standard Model: Most of the activity here is in searches for lepton flavor violation (LFV). This is motivated by the fact that many extensions of the minimal Standard Model violate lepton flavor and by the potential to access very high energy scales. For example, the tree-level exchange of a LFV vector boson of mass M_X that couples to left-handed fermions with electroweak strength and without mixing angles yields $\mathrm{B}(K_L \to \mu e) = 3.3 \times 10^{-11} (91 \text{ TeV}/M_X)^4$ [5]. This simple dimensional analysis may be used to read from Table 1 that the reaction $K_L \to \mu e$ is already probing scales of nearly 100 TeV. Table 1 summarizes the present experimental situation vis a vis LFV, along with the expected near-future progress. The decays $K_L \to \mu^{\pm} e^{\mp}$ and $K^+ \to \pi^+ e^{\mp} \mu^{\pm}$ (or $K_L \to \pi^0 e^{\mp} \mu^{\pm}$) provide complementary information on potential family number violating interactions since the former is sensitive to axial-vector (or pseudoscalar) couplings and the latter is sensitive to vector (or scalar) couplings.

Table 1: Searches for lepton flavor violation in K decay

Mode	90% CL upper limit	Exp't	Yr./Ref.	(Near-) future aim
$K^+ \to \pi^+ e \mu$	$2.1 \cdot 10^{-10}$	BNL-777	90/11	$3 \cdot 10^{-12}$ (BNL-865)
$K_L \to \mu e$	$3.3 \cdot 10^{-11}$	BNL-791	93/12	$3 \cdot 10^{-12}$ (BNL-871)
$K_L \to \pi^0 e \mu$	$3.2 \cdot 10^{-9}$	FNAL-799	94/13	$5 \cdot 10^{-11}$ (KTeV)

Another forbidden decay currently being pursued is $K^+ \to \pi^+ X^0$, where X^0 is a very light, noninteracting particle (*e.g.* hyperphoton, axion, familon, etc.). Recently the upper limit on this process has been improved to 3×10^{-10} [15]. Data already collected by BNL-787 are expected to yield a further factor in sensitivity to this process.

C. Measurements of Standard Model parameters: Until recently, searches for $K^+ \to \pi^+ \nu\overline{\nu}$ have been motivated by the possibility of observing non-SM physics because the sensitivity attained was far short of the SM prediction for this decay [16] and long-distance contributions were known to be negligible [2]. However, BNL-787 has attained the sensitivity at which the observation of an event can no longer be unambiguously attributed to non-SM physics. The previous 90% CL upper limit [14] is 2.4×10^{-9}, but running with an upgraded beam and detector BNL-787 recently observed one candidate event, corresponding to a branching ratio of $(4.2^{+9.7}_{-3.5}) \times 10^{-10}$ [15]. Further data already collected are expected to increase the sensitivity by more than a factor 2, and there are plans to collect data representing a further large increase in sensitivity. This reaction is now interesting from the point of view of constraining SM parameters. The branching ratio can be written in terms of the very well-measured rate of K_{e3} as [2]:

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) = \frac{\alpha^2 \mathrm{B}(K^+ \to \pi^o e^+ \nu)}{V_{us}^2 2\pi^2 \sin^4 \theta_W} \times \sum_{l=e,\mu,\tau} |V_{cs}^* V_{cd} X_{NL}^{\ell} + V_{ts}^* V_{td} X(m_t)|^2 \qquad (1)$$

to eliminate the *a priori* unknown hadronic matrix element. Isospin breaking corrections to the ratio of matrix elements reduce this rate by 10% [17]. In Eq. (1) the Inami-Lim function $X(m_t)$ is of order 1 [18], and X^{ℓ}_{NL} is several hundred times smaller. This form exhibits the strong dependence of this branching ratio on $|V_{td}|$. QCD corrections, which are contained in X^{ℓ}_{NL}, are relatively small and now known [10] to $\leq 10\%$. Evaluating the constants in Eq. (1) with $m_t = 175$ GeV, one can cast this result in terms of the CKM parameters A, ρ and η (see our Section on "The Cabibbo-Kobayashi-Maskawa mixing matrix") [10]

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) \approx 1.0 \times 10^{-10} A^4 [\eta^2 + (\rho_o - \rho)^2] \qquad (2)$$

where $\rho_o \equiv 1 + (\frac{2}{3}X^{e}_{NL} + \frac{1}{3}X^{\tau}_{NL})/(A^2 V^4_{us} X(m_t)) \approx 1.4$. Thus, $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu})$ determines a circle in the ρ, η plane with center $(\rho_o, 0)$ and radius $\approx \frac{1}{A^2}\sqrt{\frac{\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu})}{1.0 \times 10^{-10}}}$.

The decay $K_L \to \mu^+\mu^-$ also has a short distance contribution sensitive to the CKM parameter ρ. For $m_t = 175$ GeV it is given by [10]:

$$\mathrm{B}_{\mathrm{SD}}(K_L \to \mu^+\mu^-) \approx 1.7 \times 10^{-9} A^4 (\rho'_o - \rho)^2 \qquad (3)$$

where ρ'_o depends on the charm quark mass and is around 1.2. This decay, however, is dominated by a long-distance contribution from a two-photon intermediate state. The absorptive (imaginary) part of the long-distance component is calculated in terms of the measured rate for $K_L \to \gamma\gamma$ to be $\mathrm{B}_{\mathrm{abs}}(K_L \to \mu^+\mu^-) = (7.07 \pm 0.18) \times 10^{-9}$; and it almost completely saturates the observed rate $\mathrm{B}(K_L \to \mu^+\mu^-) = (7.2 \pm 0.5) \times 10^{-9}$ listed in the current edition. The difference between the observed rate and the absorptive component can be attributed to the (coherent) sum of the short-distance amplitude and the real part of the long-distance amplitude. In order to use this mode to constrain ρ it is, therefore, necessary to know the real part of the long-distance contribution. Unlike the absorptive part, the real part of the long-distance contribution cannot be derived from the measured rate for $K_L \to \gamma\gamma$. At present, it is not possible to compute this long-distance component reliably and, therefore, it is not possible to constrain ρ from this mode. It is expected that studies of the reactions $K_L \to \ell^+\ell^-\gamma$, and $K_L \to \ell^+\ell^-\ell'^+\ell'^-$ for $\ell, \ell' = e$ or μ will improve our understanding of the long distance effects in $K_L \to \mu^+\mu^-$ (the current data is parameterized in terms of α^*_K, discussed on page 24 of the K^0_L Particle Properties Listing in our 1997 WWW update).

D. Searches for CP violation: The mode $K_L \to \pi^0\nu\overline{\nu}$ is dominantly CP-violating and free of hadronic uncertainties [2,19]. The Standard Model predicts a branching ratio $\sim 10^{-11} - 10^{-10}$; for $m_t = 175$ GeV it is given approximately by [10]:

$$\mathrm{B}(K_L \to \pi^0\nu\overline{\nu}) \approx 4.1 \times 10^{-10} A^4 \eta^2 \ . \qquad (4)$$

The current published upper bound is $\mathrm{B}(K_L \to \pi^0\nu\overline{\nu}) \leq 5.8 \times 10^{-5}$ [20] and KTeV (FNAL799II) is expected to place a bound of order 10^{-8} [21]. The KTeV group has recently quoted a preliminary result of 1.8×10^{-6} [22]. If lepton flavor is conserved, the 90% CL bound on $K^+ \to \pi^+\nu\overline{\nu}$ provides the model independent bound $B(K_L \to \pi^0\nu\overline{\nu}) < 1.1 \times 10^{-8}$ [23]. A recent proposal, BNL-926 [24], aims to make a $\sim 15\%$ measurement of $\mathrm{B}(K_L \to \pi^0\nu\overline{\nu})$. There is also a Fermilab EOI [25] with comparable goals.

The decay $K_L \to \pi^0 e^+e^-$ also has sensitivity to the product $A^4\eta^2$. It has a direct CP-violating component that depends on the value of the top-quark mass, and that for $m_t = 175$ GeV is given by [10]:

$$\mathrm{B}_{\mathrm{dir}}(K_L \to \pi^0 e^+e^-) \approx 6.7 \times 10^{-11} A^4 \eta^2 \ . \qquad (5)$$

However, like $K_L \to \mu^+\mu^-$ this mode suffers from large theoretical uncertainties due to long distance strong interaction effects. It has an indirect CP-violating component given by:

$$\mathrm{B}_{\mathrm{ind}}(K_L \to \pi^0 e^+e^-) = |\epsilon|^2 \frac{\tau_{K_L}}{\tau_{K_S}} \mathrm{B}(K_S \to \pi^0 e^+e^-) \ , \qquad (6)$$

that has been estimated to be less than 10^{-12} [26], but that will not be known precisely until a measurement of $K_S \to \pi^0 e^+e^-$ is available [4,27]. There is also a CP-conserving component dominated by a two-photon intermediate state that cannot be computed reliably at present. This component has an absorptive part that can be, in principle, determined from a detailed analysis of $K_L \to \pi^0\gamma\gamma$.

An analysis of $K_L \to \pi^0\gamma\gamma$ within chiral perturbation theory has been carried out in terms of a parameter a_V [28] that determines both the rate and the shape of the distribution $d\Gamma/dm_{\gamma\gamma}$. A fit to the distribution has given $-0.32 < a_V < 0.19$ [29]; a value that suggests that the absorptive part of the CP-conserving contribution to $K_L \to \pi^0 e^+e^-$ is significantly smaller than the direct CP-violating component [29]. However, there remains some uncertainty in the interpretation of $K_L \to \pi^0\gamma\gamma$ in terms of a_V. Analyses that go beyond chiral perturbation theory have found larger values of a_V, helping with understanding the rate in that process [30]. This would indicate a sizeable CP-conserving component to $K_L \to \pi^0 e^+e^-$. The real part of the CP-conserving contribution to $K_L \to \pi^0 e^+e^-$ is also unknown. The related process, $K_L \to \pi^0\gamma e^+e^-$, is an additional background in some region of phase space [31].

Finally, BNL-845 observed a potential background to $K_L \to \pi^0 e^+e^-$ from the decay $K_L \to \gamma\gamma e^+e^-$ [32]. This was later confirmed with an order of magnitude larger sample by FNAL-799 [33], which measured additional kinematic quantities. It has been estimated that this background will enter at the level of 10^{-11} [34], comparable to the signal level. Because of this, the observation of $K_L \to \pi^0 e^+e^-$ will depend on background subtraction with good statistics.

The current upper bound for the process $K_L \to \pi^0 e^+e^-$ is 4.3×10^{-9} [35]. For the closely related muonic process, the upper bound is $\mathrm{B}(K_L \to \pi^0\mu^+\mu^-) \leq 5.1 \times 10^{-9}$ [36]. KTeV expects to reach a sensitivity of roughly 10^{-11} for both reactions [21].

E. Other long distance dominated modes: The decays $K^+ \to \pi^+\ell^+\ell^-$ ($\ell = e$ or μ) are described by chiral perturbation theory in terms of one parameter, ω^+ [37]. This parameter determines both the rate and distribution $d\Gamma/dm_{\ell\ell}$ for these processes. A careful study of these two reactions can provide a measurement of ω^+ and a test of the chiral perturbation theory description. A simultaneous fit to the rate and spectrum of $K^+ \to \pi^+e^+e^-$ gives: $\omega^+ = 0.89^{+0.24}_{-0.14}$; $B(K^+ \to \pi^+e^+e^-) = (2.99 \pm 0.22) \times 10^{-7}$ [38]. These two results satisfy the prediction of chiral perturbation theory within two standard deviations [4]. Improved statistics for this mode and a measurement of the mode $K^+ \to \pi^+\mu^+\mu^-$ are thus desired. BNL-787 has recently measured $B(K^+ \to \pi^+\mu^+\mu^-) = (5.0 \pm 1.0) \times 10^{-8}$ [39] which is at about the predicted level, but the result is not yet accurate enough to provide additional constraints.

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K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\mu^+\nu_\mu$		(63.51 ± 0.18) %	S=1.3
Γ_2	$e^+\nu_e$		$(1.55 \pm 0.07) \times 10^{-5}$	
Γ_3	$\pi^+\pi^0$		(21.16 ± 0.14) %	S=1.1
Γ_4	$\pi^+\pi^+\pi^-$		(5.59 ± 0.05) %	S=1.8
Γ_5	$\pi^+\pi^0\pi^0$		(1.73 ± 0.04) %	S=1.2
Γ_6	$\pi^0\mu^+\nu_\mu$		(3.18 ± 0.08) %	S=1.5
	Called $K^+_{\mu 3}$.			
Γ_7	$\pi^0e^+\nu_e$		(4.82 ± 0.06) %	S=1.3
	Called K^+_{e3}.			
Γ_8	$\pi^0\pi^0e^+\nu_e$		$(2.1 \pm 0.4) \times 10^{-5}$	
Γ_9	$\pi^+\pi^-e^+\nu_e$		$(3.91 \pm 0.17) \times 10^{-5}$	
Γ_{10}	$\pi^+\pi^-\mu^+\nu_\mu$		$(1.4 \pm 0.9) \times 10^{-5}$	
Γ_{11}	$\pi^0\pi^0\pi^0e^+\nu_e$		$< 3.5 \times 10^{-6}$	CL=90%
Γ_{12}	$\pi^+\gamma\gamma$	[a]	$(1.10 \pm 0.32) \times 10^{-6}$	
Γ_{13}	$\pi^+3\gamma$	[a]	$< 1.0 \times 10^{-4}$	CL=90%
Γ_{14}	$\mu^+\nu_\mu\nu\bar{\nu}$		$< 6.0 \times 10^{-6}$	CL=90%
Γ_{15}	$e^+\nu_e\nu\bar{\nu}$		$< 6 \times 10^{-5}$	CL=90%
Γ_{16}	$\mu^+\nu_\mu e^+e^-$		$(1.3 \pm 0.4) \times 10^{-7}$	
Γ_{17}	$e^+\nu_e e^+e^-$		$(3.0 {}^{+3.0}_{-1.5}) \times 10^{-8}$	
Γ_{18}	$\mu^+\nu_\mu\mu^+\mu^-$		$< 4.1 \times 10^{-7}$	CL=90%
Γ_{19}	$\mu^+\nu_\mu\gamma$	[a,b]	$(5.50 \pm 0.28) \times 10^{-3}$	
Γ_{20}	$\pi^+\pi^0\gamma$	[a,b]	$(2.75 \pm 0.15) \times 10^{-4}$	
Γ_{21}	$\pi^+\pi^0\gamma$(DE)	[a,c]	$(1.8 \pm 0.4) \times 10^{-5}$	
Γ_{22}	$\pi^+\pi^+\pi^-\gamma$	[a,b]	$(1.04 \pm 0.31) \times 10^{-4}$	
Γ_{23}	$\pi^+\pi^0\pi^0\gamma$	[a,b]	$(7.5 {}^{+5.5}_{-3.0}) \times 10^{-6}$	
Γ_{24}	$\pi^0\mu^+\nu_\mu\gamma$	[a,b]	$< 6.1 \times 10^{-5}$	CL=90%
Γ_{25}	$\pi^0e^+\nu_e\gamma$	[a,b]	$(2.62 \pm 0.20) \times 10^{-4}$	
Γ_{26}	$\pi^0e^+\nu_e\gamma$(SD)	[d]	$< 5.3 \times 10^{-5}$	CL=90%
Γ_{27}	$\pi^0\pi^0e^+\nu_e\gamma$		$< 5 \times 10^{-6}$	CL=90%

Lepton Family number (*LF*), Lepton number (*L*), $\Delta S = \Delta Q$ (*SQ*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes

Γ_{28}	$\pi^+\pi^+e^-\overline{\nu}_e$	*SQ*	< 1.2	$\times 10^{-8}$	CL=90%
Γ_{29}	$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	*SQ*	< 3.0	$\times 10^{-6}$	CL=95%
Γ_{30}	$\pi^+e^+e^-$	*S1*	(2.74±0.23)	$\times 10^{-7}$	
Γ_{31}	$\pi^+\mu^+\mu^-$	*S1*	(5.0 ±1.0)	$\times 10^{-8}$	
Γ_{32}	$\pi^+\nu\overline{\nu}$	*S1*	($4.2\ ^{+9.7}_{-3.5}$)	$\times 10^{-10}$	
Γ_{33}	$\mu^-\nu e^+e^+$	*LF*	< 2.0	$\times 10^{-8}$	CL=90%
Γ_{34}	$\mu^+\nu_e$	*LF*	[e] < 4	$\times 10^{-3}$	CL=90%
Γ_{35}	$\pi^+\mu^+e^-$	*LF*	< 2.1	$\times 10^{-10}$	CL=90%
Γ_{36}	$\pi^+\mu^-e^+$	*LF*	< 7	$\times 10^{-9}$	CL=90%
Γ_{37}	$\pi^-\mu^+e^+$	*L*	< 7	$\times 10^{-9}$	CL=90%
Γ_{38}	$\pi^-e^+e^+$	*L*	< 1.0	$\times 10^{-8}$	CL=90%
Γ_{39}	$\pi^-\mu^+\mu^+$	*L*	[e] < 1.5	$\times 10^{-4}$	CL=90%
Γ_{40}	$\mu^+\overline{\nu}_e$	*L*	[e] < 3.3	$\times 10^{-3}$	CL=90%
Γ_{41}	$\pi^0e^+\overline{\nu}_e$	*L*	< 3	$\times 10^{-3}$	CL=90%
Γ_{42}	$\pi^+\gamma$				

[a] See the Particle Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] Direct-emission branching fraction.

[d] Structure-dependent part.

[e] Derived from an analysis of neutrino-oscillation experiments.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 2 decay rate, and 20 branching ratios uses 60 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 78.1$ for 53 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i\delta p_j\right\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−58						
x_4	−41	−12					
x_5	−27	−4	21				
x_6	−48	−17	14	2			
x_7	−50	−16	34	6	39		
x_8	−3	−1	2	0	2	6	
Γ	7	2	−18	−4	−2	−6	0
	x_1	x_3	x_4	x_5	x_6	x_7	x_8

	Mode	Rate (10^8 s^{-1})	Scale factor
Γ_1	$\mu^+\nu_\mu$	0.5128 ±0.0018	1.5
Γ_3	$\pi^+\pi^0$	0.1708 ±0.0012	1.1
Γ_4	$\pi^+\pi^+\pi^-$	0.0452 ±0.0004	1.8
Γ_5	$\pi^+\pi^0\pi^0$	0.01399±0.00032	1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K^+_{\mu 3}$.	0.0257 ±0.0006	1.5
Γ_7	$\pi^0e^+\nu_e$ Called K^+_{e3}.	0.0389 ±0.0005	1.3
Γ_8	$\pi^0\pi^0e^+\nu_e$	$(1.69\ ^{+0.34}_{-0.29}) \times 10^{-5}$	

$K^{\pm}$ DECAY RATES

$\Gamma(\mu^+\nu_\mu)$ Γ_1

VALUE (10^6 s^{-1})	*DOCUMENT ID*		*TECN*	*CHG*
51.28±0.18 OUR FIT Error includes scale factor of 1.5.				
51.2 ±0.8	FORD	67	CNTR	±

$\Gamma(\pi^+\pi^+\pi^-)$ Γ_4

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
4.52 ±0.04 OUR FIT Error includes scale factor of 1.8.					
4.511±0.024		[6] FORD	70	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.529±0.032	3.2M	[6] FORD	70	ASPK	
4.496±0.030		[6] FORD	67	CNTR	±

[6] First FORD 70 value is second FORD 70 combined with FORD 67.

$(\Gamma(K^+) - \Gamma(K^-))\ /\ \Gamma(K)$

$K^{\pm} \to \mu^{\pm}\nu_\mu$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	*DOCUMENT ID*		*TECN*
−0.54±0.41	FORD	67	CNTR

$K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
0.07±0.12 OUR AVERAGE					
0.08±0.12		[7] FORD	70	ASPK	
−0.50±0.90		FLETCHER	67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.02±0.16		[8] SMITH	73	ASPK	±
0.10±0.14	3.2M	[7] FORD	70	ASPK	
−0.04±0.21		[7] FORD	67	CNTR	

[7] First FORD 70 value is second FORD 70 combined with FORD 67.

[8] SMITH 73 value of $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ rate difference is derived from SMITH 73 value of $K^{\pm} \to \pi^{\pm}2\pi^0$ rate difference.

$K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
0.0 ±0.6 OUR AVERAGE					
0.08±0.58		SMITH	73	ASPK	±
−1.1 ±1.8	1802	HERZO	69	OSPK	

$K^{\pm} \to \pi^{\pm}\pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	*DOCUMENT ID*		*TECN*
0.8±1.2	HERZO	69	OSPK

$K^{\pm} \to \pi^{\pm}\pi^0\gamma$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.9± 3.3 OUR AVERAGE						
0.8± 5.8	2461	SMITH	76	WIRE	±	E_π 55–90 MeV
1.0± 4.0	4000	ABRAMS	73B	ASPK	±	E_π 51–100 MeV
0.0±24.0	24	EDWARDS	72	OSPK		E_π 58–90 MeV

K^+ BRANCHING RATIOS

$\Gamma(\mu^+\nu_\mu)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
63.51±0.18 OUR FIT Error includes scale factor of 1.3.						
63.24±0.44	62k	CHIANG	72	OSPK	+	1.84 GeV/*c* K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
56.9 ±2.6		[9] ALEXANDER	57	EMUL	+	
58.5 ±3.0		[9] BIRGE	56	EMUL	+	

[9] Old experiments not included in averaging.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_1/Γ_4

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
11.35±0.12 OUR FIT Error includes scale factor of 1.8.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
10.38±0.82	427	[10] YOUNG	65	EMUL	+

[10] Deleted from overall fit because YOUNG 65 constrains his results to add up to 1. Only YOUNG 65 measured $(\mu\nu)$ directly.

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$2.1^{+1.8}_{-1.3}$		4	BOWEN	67B	OSPK	+
<160.0	95		BORREANI	64	HBC	+

$\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ Γ_2/Γ_1

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
2.45±0.11 OUR AVERAGE					
2.51±0.15	404	HEINTZE	76	SPEC	+
2.37±0.17	534	HEARD	75B	SPEC	+
2.42±0.42	112	CLARK	72	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.8\ ^{+0.8}_{-0.6}$	8	MACEK	69	ASPK	+
$1.9\ ^{+0.7}_{-0.5}$	10	BOTTERILL	67	ASPK	+

$\Gamma(\pi^+\pi^0)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
21.16±0.14 OUR FIT Error includes scale factor of 1.1.					
21.18±0.28	16k	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
21.0 ±0.6		CALLAHAN 65	HLBC		See $\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$
21.6 ±0.6		TRILLING 65B	RVUE		
23.2 ±2.2		[11] ALEXANDER 57	EMUL	+	
27.7 ±2.7		[11] BIRGE 56	EMUL	+	

[11] Earlier experiments not averaged.

$\Gamma(\pi^+\pi^0)/\Gamma(\mu^+\nu_\mu)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.3331±0.0028 OUR FIT Error includes scale factor of 1.1.					
0.3316±0.0032 OUR AVERAGE					
0.3329±0.0047±0.0010	45k	USHER 92	SPEC	+	$p\overline{p}$ at rest
0.3355±0.0057		[12] WEISSENBE... 76	SPEC	+	
0.305 ±0.018	1600	ZELLER 69	ASPK	+	
0.3277±0.0065	4517	[13] AUERBACH 67	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.328 ±0.005	25k	[12] WEISSENBE... 74	STRC	+	

[12] WEISSENBERG 76 revises WEISSENBERG 74.

[13] AUERBACH 67 changed from 0.3253 ± 0.0065. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$.

$\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_3/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG
3.78±0.04 OUR FIT Error includes scale factor of 1.5.				
3.84±0.27 OUR AVERAGE Error includes scale factor of 1.9.				
3.96±0.15	1045	CALLAHAN 66	FBC	+
3.24±0.34	134	YOUNG 65	EMUL	+

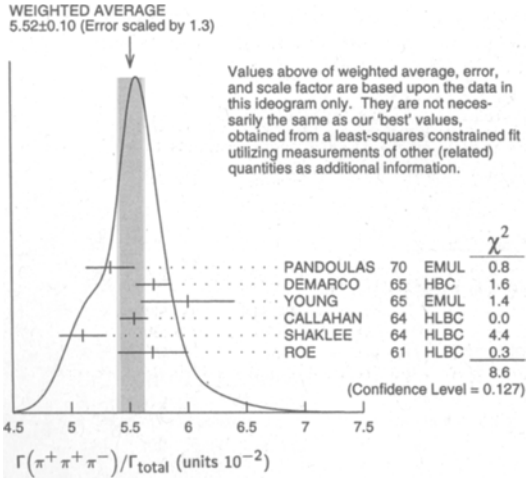
$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
5.59±0.05 OUR FIT Error includes scale factor of 1.8.					
5.52±0.10 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
5.34±0.21	693	[14] PANDOULAS 70	EMUL	+	
5.71±0.15		DEMARCO 65	HBC		
6.0 ±0.4	44	YOUNG 65	EMUL	+	
5.54±0.12	2332	CALLAHAN 64	HLBC	+	
5.1 ±0.2	540	SHAKLEE 64	HLBC	+	
5.7 ±0.3		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.56±0.20	2330	[15] CHIANG 72	OSPK	+	1.84 GeV/c K^+
5.2 ±0.3		[16] TAYLOR 59	EMUL	+	
6.8 ±0.4		[16] ALEXANDER 57	EMUL	+	
5.6 ±0.4		[16] BIRGE 56	EMUL	+	

[14] Includes events of TAYLOR 59.

[15] Value is not independent of CHIANG 72 $\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$, $\Gamma(\pi^+\pi^0)/\Gamma_{\rm total}$, $\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$, $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{\rm total}$, and $\Gamma(\pi^0 e^+\nu_e)/\Gamma_{\rm total}$.

[16] Earlier experiments not averaged.

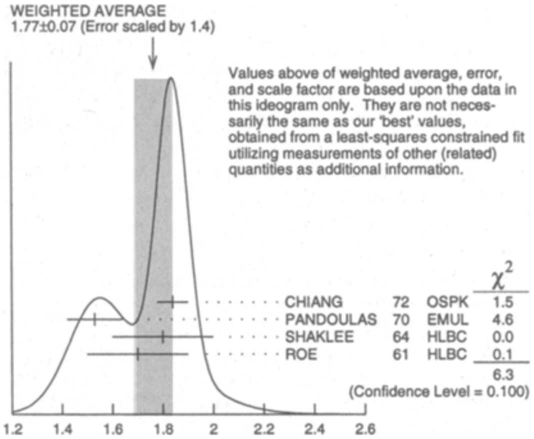


$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.73±0.04 OUR FIT Error includes scale factor of 1.2.					
1.77±0.07 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1.84±0.06	1307	CHIANG 72	OSPK	+	1.84 GeV/c K^+
1.53±0.11	198	[17] PANDOULAS 70	EMUL	+	
1.8 ±0.2	108	SHAKLEE 64	HLBC	+	
1.7 ±0.2		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.2		[18] TAYLOR 59	EMUL	+	
2.2 ±0.4		[18] ALEXANDER 57	EMUL	+	
2.1 ±0.5		[18] BIRGE 56	EMUL	+	

[17] Includes events of TAYLOR 59.

[18] Earlier experiments not averaged.



$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^0)$ Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.0619±0.0020 OUR FIT Error includes scale factor of 1.2.					
0.061 ±0.005	574	[19] LUCAS 73B	HBC	−	Dalitz pairs only

[19] LUCAS 73B gives N($\pi 2\pi^0$) = 574 ± 5.9%, N(2π) = 3564 ± 3.1%. We quote 0.5N($\pi 2\pi^0$)/N(2π) where 0.5 is because only Dalitz pair π^0's were used.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_5/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.310±0.007 OUR FIT Error includes scale factor of 1.2.					
0.304±0.009 OUR AVERAGE					
0.303±0.009	2027	BISI 65	BC	+	HBC+HLBC
0.393±0.099	17	YOUNG 65	EMUL	+	

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{\rm total}$ Γ_6/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
3.18±0.08 OUR FIT Error includes scale factor of 1.5.					
3.33±0.16	2345	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.8 ±0.4		[20] TAYLOR 59	EMUL	+	
5.9 ±1.3		[20] ALEXANDER 57	EMUL	+	
2.8 ±1.0		[20] BIRGE 56	EMUL	+	

[20] Earlier experiments not averaged.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$ Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.0501±0.0013 OUR FIT Error includes scale factor of 1.5.				
0.0488±0.0026 OUR AVERAGE				
0.054 ±0.009	240	ZELLER 69	ASPK	+
0.0480±0.0037	424	[21] GARLAND 68	OSPK	+
0.0486±0.0040	307	[22] AUERBACH 67	OSPK	+

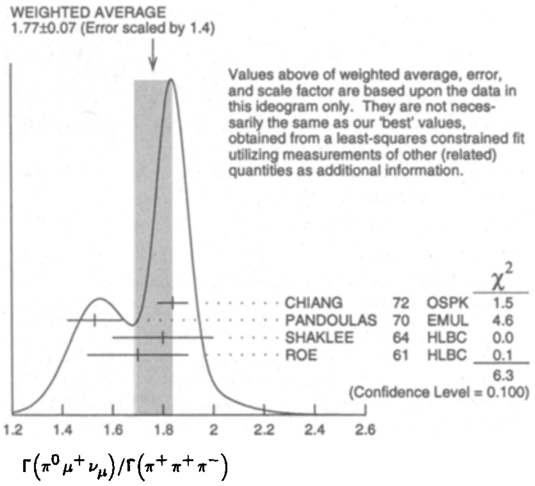
[21] GARLAND 68 changed from 0.055 ± 0.004 in agreement with μ-spectrum calculation of GAILLARD 70 appendix B. L.G.Pondrom, (private communication 73).

[22] AUERBACH 67 changed from 0.0602 ± 0.0046 by erratum which brings the μ-spectrum calculation into agreement with GAILLARD 70 appendix B.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_6/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.569±0.014 OUR FIT Error includes scale factor of 1.5.					
0.517±0.032 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
0.503±0.019	1505	[23] HAIDT 71	HLBC	+	
0.63 ±0.07	2845	[24] BISI 65B	BC	+	HBC+HLBC
0.90 ±0.16	38	YOUNG 65	EMUL	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.510±0.017	1505	[23] EICHTEN 68	HLBC	+	

[23] HAIDT 71 is a reanalysis of EICHTEN 68.
[24] Error enlarged for background problems. See GAILLARD 70.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0 e^+\nu_e)$ Γ_6/Γ_7

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.660±0.015 OUR FIT Error includes scale factor of 1.5.					
0.680±0.013 OUR AVERAGE					
0.705±0.063	554	[25] LUCAS 73B	HBC	−	Dalitz pairs only
0.698±0.025	3480	[26] CHIANG 72	OSPK	+	1.84 GeV/c K^+
0.667±0.017	5601	BOTTERILL 68B	ASPK	+	
0.703±0.056	1509	[27] CALLAHAN 66B	HLBC		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.670±0.014		[28] HEINTZE 77	SPEC	+	
0.67 ±0.12		WEISSENBE... 76	SPEC	+	
0.608±0.014	1585	[29] BRAUN 75	HLBC	+	
0.596±0.025		[30] HAIDT 71	HLBC	+	
0.604±0.022	1398	[30] EICHTEN 68	HLBC		

[25] LUCAS 73B gives $N(K_{\mu3}) = 554 \pm 7.6\%$, $N(K_{e3}) = 786 \pm 3.1\%$. We divide.
[26] CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0 e^+\nu_e)$ is statistically independent of CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{\rm total}$ and $\Gamma(\pi^0 e^+\nu_e)/\Gamma_{\rm total}$.
[27] From CALLAHAN 66B we use only the $K_{\mu3}/K_{e3}$ ratio and do not include in the fit the ratios $K_{\mu3}/(\pi\pi^+\pi^0)$ and $K_{e3}/(\pi\pi^+\pi^0)$, since they show large disagreements with the rest of the data.
[28] HEINTZE 77 value from fit to λ_0. Assumes μ-e universality.
[29] BRAUN 75 value is from form factor fit. Assumes μ-e universality.
[30] HAIDT 71 is a reanalysis of EICHTEN 68. Only individual ratios included in fit (see $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ and $\Gamma(\pi^0 e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$).

$[\Gamma(\pi^+\pi^0)+\Gamma(\pi^0\mu^+\nu_\mu)]/\Gamma_{\rm total}$ $(\Gamma_3+\Gamma_6)/\Gamma$

We combine these two modes for experiments measuring them in xenon bubble chamber because of difficulties of separating them there.

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
24.34±0.15 OUR FIT Error includes scale factor of 1.2.				
24.6 ±1.0 OUR AVERAGE Error includes scale factor of 1.4.				
25.4 ±0.9	886	SHAKLEE 64	HLBC	+
23.4 ±1.1		ROE 61	HLBC	+

$\Gamma(\pi^0 e^+\nu_e)/\Gamma_{\rm total}$ Γ_7/Γ

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
4.82±0.06 OUR FIT Error includes scale factor of 1.3.					
4.85±0.09 OUR AVERAGE					
4.86±0.10	3516	CHIANG 72	OSPK	+	1.84 GeV/c K^+
4.7 ±0.3	429	SHAKLEE 64	HLBC	+	
5.0 ±0.5		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.1 ±1.3		[31] ALEXANDER 57	EMUL	+	
3.2 ±1.3		[31] BIRGE 56	EMUL	+	

[31] Earlier experiments not averaged.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ Γ_7/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.0759±0.0011 OUR FIT Error includes scale factor of 1.4.				
0.0752±0.0024 OUR AVERAGE				
0.069 ±0.006	350	ZELLER 69	ASPK	+
0.0775±0.0033	960	BOTTERILL 68C	ASPK	+
0.069 ±0.006	561	GARLAND 68	OSPK	+
0.0791±0.0054	295	[32] AUERBACH 67	OSPK	+

[32] AUERBACH 67 changed from 0.0797 ± 0.0054. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$. The value 0.0785 ± 0.0025 given in AUERBACH 67 is an average of AUERBACH 67 $\Gamma(\pi^0 e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ and CESTER 66 $\Gamma(\pi^0 e^+\nu_e)/[\Gamma(\mu^+\nu_\mu)+\Gamma(\pi^+\pi^0)]$.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\pi^+\pi^0)$ Γ_7/Γ_3

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.2280±0.0035 OUR FIT Error includes scale factor of 1.3.					
0.221 ±0.012	786	[33] LUCAS 73B	HBC	−	Dalitz pairs only

[33] LUCAS 73B gives $N(K_{e3}) = 786 \pm 3.1\%$, $N(2\pi) = 3564 \pm 3.1\%$. We divide.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_7/Γ_4

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.862±0.011 OUR FIT Error includes scale factor of 1.3.				
0.860±0.014 OUR AVERAGE				
0.867±0.027	2768	BARMIN 87	XEBC	+
0.856±0.040	2827	BRAUN 75	HLBC	+
0.850±0.019	4385	[34] HAIDT 71	HLBC	+
0.94 ±0.09	854	BELLOTTI 67B	HLBC	
0.90 ±0.06	230	BORREANI 64	HBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.846±0.021	4385	[34] EICHTEN 68	HLBC	+
0.90 ±0.16	37	YOUNG 65	EMUL	+

[34] HAIDT 71 is a reanalysis of EICHTEN 68.

$\Gamma(\pi^0 e^+\nu_e)/[\Gamma(\mu^+\nu_\mu)+\Gamma(\pi^+\pi^0)]$ $\Gamma_7/(\Gamma_1+\Gamma_3)$

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
5.70±0.08 OUR FIT Error includes scale factor of 1.4.				
6.01±0.15 OUR AVERAGE				
5.92±0.65		[35] WEISSENBE... 76	SPEC	+
6.16±0.22	5110	ESCHSTRUTH 68	OSPK	+
5.89±0.21	1679	CESTER 66	OSPK	+

[35] Value calculated from WEISSENBERG 76 $(\pi^0 e\nu)$, $(\mu\nu)$, and $(\pi\pi^0)$ values to eliminate dependence on our 1974 $(\pi 2\pi^0)$ and $(\pi\pi^+\pi^-)$ fractions.

$\Gamma(\pi^0\pi^0 e^+\nu_e)/\Gamma(\pi^0 e^+\nu_e)$ Γ_8/Γ_7

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
$4.3^{+0.9}_{-0.7}$ OUR FIT					
$4.1^{+1.0}_{-0.7}$ OUR AVERAGE					
$4.2^{+1.0}_{-0.9}$		25	BOLOTOV 86B	CALO	−
$3.8^{+5.0}_{-1.2}$		2	LJUNG 73	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<37.0	90	0	ROMANO 71	HLBC	+

$\Gamma(\pi^0\pi^0 e^+\nu_e)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
2.1 ±0.4 OUR FIT				
2.54±0.89	10	BARMIN 88B	HLBC	+

$\Gamma(\pi^+\pi^- e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_9/Γ_4

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
6.99±0.30 OUR AVERAGE Error includes scale factor of 1.2.				
7.21±0.32	30k	ROSSELET 77	SPEC	+
7.36±0.68	500	BOURQUIN 71	ASPK	
7.0 ±0.9	106	SCHWEINB... 71	HLBC	+
5.83±0.63	269	ELY 69	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.7 ±1.5	69	BIRGE 65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.77^{+0.54}_{-0.50}$	1	CLINE 65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{10}/Γ_4

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
2.57±1.55	7	BISI 67	DBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2.5	1	GREINER 64	EMUL	+

$\Gamma(\pi^0\pi^0\pi^0 e^+\nu_e)/\Gamma_{\rm total}$ Γ_{11}/Γ

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<3.5	90	0	BOLOTOV 88	SPEC	−
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9	90	0	BARMIN 92	XEBC	+

$\Gamma(\pi^+\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{12}/Γ

All values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
11 ± 3 ±1		31	[36] KITCHING 97	B787		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 10	90	0	ATIYA 90B	B787		Tπ 117–127 MeV
< 84	90	0	ASANO 82	CNTR	+	Tπ 117–127 MeV
−420 ±520		0	ABRAMS 77	SPEC	+	Tπ <92 MeV
< 350	90	0	LJUNG 73	HLBC,	+	6–102, 114–127 MeV
< 500	90	0	KLEMS 71	OSPK	+	Tπ <117 MeV
−100 ±600			CHEN 68	OSPK	+	Tπ 60–90 MeV

[36] KITCHING 97 is extrapolated from their model-independent branching fraction $(6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$ for 100 MeV/c<P_{π^+} < 180 MeV/c using Chiral Perturbation Theory.

$\Gamma(\pi^+ 3\gamma)/\Gamma_{\text{total}}$ Γ_{13}/Γ

Values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<1.0	90	ASANO 82	CNTR	+	$T(\pi)$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.0	90	KLEMS 71	OSPK	+	$T(\pi)$ >117 MeV

$\Gamma(\mu^+\nu_\mu\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	CHG
<6.0	90	0	[37] PANG 73	CNTR	+

[37] PANG 73 assumes μ spectrum from ν-ν interaction of BARDIN 70.

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma(e^+\nu_e)$ Γ_{15}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG
<3.8	90	0	HEINTZE 79	SPEC	+

$\Gamma(\mu^+\nu_\mu e^+e^-)/\Gamma(\pi^+\pi^- e^+\nu_e)$ Γ_{16}/Γ_9

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
3.3±0.9	14	[38] DIAMANT-... 76	SPEC	+	$m_{e^+e^-}$ >140 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
27. ±8.	14	[38] DIAMANT-... 76	SPEC	+	Extrapolated BR

[38] DIAMANT-BERGER 76 gives this result times our 1975 $\pi^+\pi^- e\nu$ BR ratio. The second DIAMANT-BERGER 76 value is the first value extrapolated to 0 to include low mass e^+e^- pairs. More recent calculations (BIJNENS 93) of this extrapolation disagree with those of DIAMANT-BERGER 76.

$\Gamma(e^+\nu_e e^+e^-)/\Gamma(\pi^+\pi^- e^+\nu_e)$ Γ_{17}/Γ_9

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$0.76^{+0.76}_{-0.38}$	4	[39] DIAMANT-... 76	SPEC	+	$m_{e^+e^-}$ >140 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5.4\ ^{+5.4}_{-2.7}$	4	[39] DIAMANT-... 76	SPEC	+	Extrapolated BR

[39] DIAMANT-BERGER 76 gives this result times our 1975 $\pi^+\pi^- e\nu$ BR ratio. The second DIAMANT-BERGER 76 value is the first value extrapolated to 0 to include low mass e^+e^- pairs. More recent calculations (BIJNENS 93) of this extrapolation disagree with those of DIAMANT-BERGER 76.

$\Gamma(\mu^+\nu_\mu\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID	TECN	CHG
<4.1	90	ATIYA 89	B787	+

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
5.50±0.28 OUR AVERAGE					
6.6 ±1.5		[40,41] DEMIDOV 90	XEBC		$P(\mu)$ <231.5 MeV/c
6.0 ±0.9		BARMIN 88	HLBC	+	$P(\mu)$ <231.5 MeV/c
5.4 ±0.3		[42] AKIBA 85	SPEC		$P(\mu)$ <231.5 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.5 ±0.8		[41,43] DEMIDOV 90	XEBC		$E(\gamma)$ > 20 MeV
3.2 ±0.5	57	[44] BARMIN 88	HLBC	+	$E(\gamma)$ >20 MeV
5.8 ±3.5	12	WEISSENBE... 74	STRC	+	$E(\gamma)$ >9 MeV

[40] $P(\mu)$ cut given in DEMIDOV 90 paper, 235.1 MeV/c, is a misprint according to authors (private communication).

[41] DEMIDOV 90 quotes only inner bremsstrahlung (IB) part.

[42] Assumes μ-e universality and uses constraints from $K \rightarrow e\nu\gamma$.

[43] Not independent of above DEMIDOV 90 value. Cuts differ.

[44] Not independent of above BARMIN 88 value. Cuts differ.

$\Gamma(\pi^+\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
2.75±0.15 OUR AVERAGE						
2.71±0.45		140	BOLOTOV 87	WIRE	−	$T\pi^-$ 55–90 MeV
2.87±0.32		2461	SMITH 76	WIRE	±	$T\pi^\pm$ 55–90 MeV
2.71±0.19		2100	ABRAMS 72	ASPK	±	$T\pi^+$ 55–90 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$1.5\ ^{+1.1}_{-0.6}$			[45] LJUNG 73	HLBC	+	$T\pi^+$ 55–80 MeV
$2.6\ ^{+1.5}_{-1.1}$			[45] LJUNG 73	HLBC	+	$T\pi^+$ 55–90 MeV
$6.8\ ^{+3.7}_{-2.1}$		17	[45] LJUNG 73	HLBC	+	$T\pi^+$ 55–102 MeV
2.4 ±0.8		24	EDWARDS 72	OSPK		$T\pi^+$ 58–90 MeV
<1.0		0	[46] MALTSEV 70	HLBC	+	$T\pi^+$ <55 MeV
<1.9	90	0	EMMERSON 69	OSPK		$T\pi^+$ 55–80 MeV
2.2 ±0.7		18	CLINE 64	FBC	+	$T\pi^+$ 55–80 MeV

[45] The LJUNG 73 values are not independent.

[46] MALTSEV 70 selects low π^+ energy to enhance direct emission contribution.

$\Gamma(\pi^+\pi^0\gamma(\text{DE}))/\Gamma_{\text{total}}$ Γ_{21}/Γ

Direct emission part of $\Gamma(\pi^+\pi^0\gamma)/\Gamma_{\text{total}}$.

VALUE (units 10^{-5})	DOCUMENT ID	TECN	CHG	COMMENT
1.8 ±0.4 OUR AVERAGE				
$2.05\pm0.46^{+0.39}_{-0.23}$	BOLOTOV 87	WIRE	−	$T\pi^-$ 55–90 MeV
2.3 ±3.2	SMITH 76	WIRE	±	$T\pi^\pm$ 55–90 MeV
1.56±0.35±0.5	ABRAMS 72	ASPK	±	$T\pi^\pm$ 55–90 MeV

$\Gamma(\pi^+\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.04±0.31 OUR AVERAGE					
1.10±0.48	7	BARMIN 89	XEBC		$E(\gamma)$ > 5 MeV
1.0 ±0.4		STAMER 65	EMUL	+	$E(\gamma)$ >11 MeV

$\Gamma(\pi^+\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^0\pi^0)$ Γ_{23}/Γ_5

VALUE (units 10^{-4})	DOCUMENT ID	TECN	CHG	COMMENT
$4.3^{+3.2}_{-1.7}$	BOLOTOV 85	SPEC	−	$E(\gamma)$ > 10 MeV

$\Gamma(\pi^0\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<6.1	90	0	LJUNG 73	HLBC	+	$E(\gamma)$ >30 MeV

$\Gamma(\pi^0 e^+\nu_e\gamma)/\Gamma(\pi^0 e^+\nu_e)$ Γ_{25}/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.54±0.04 OUR AVERAGE Error includes scale factor of 1.1.					
0.46±0.08	82	[47] BARMIN 91	XEBC		$E(\gamma)$ > 10 MeV, 0.6 < $\cos\theta_e\ \gamma$ < 0.9
0.56±0.04	192	[48] BOLOTOV 86B	CALO	−	$E(\gamma)$ >10 MeV
0.76±0.28	13	[49] ROMANO 71	HLBC		$E(\gamma)$ >10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.51±0.25	82	[47] BARMIN 91	XEBC		$E(\gamma)$ > 10 MeV, $\cos\theta_e\ \gamma$ < 0.98
0.48±0.20	16	[50] LJUNG 73	HLBC	+	$E(\gamma)$ >30 MeV
$0.22^{+0.15}_{-0.10}$		[50] LJUNG 73	HLBC	+	$E(\gamma)$ >30 MeV
0.53±0.22		[49] ROMANO 71	HLBC	+	$E(\gamma)$ >30 MeV
1.2 ±0.8		BELLOTTI 67	HLBC	+	$E(\gamma)$ >30 MeV

[47] BARMIN 91 quotes branching ratio $\Gamma(K \rightarrow e\pi^0\nu\gamma)/\Gamma_{\text{all}}$. The measured normalization is $[\Gamma(K \rightarrow e\pi^0\nu) + \Gamma(K \rightarrow \pi^+\pi^+\pi^-)]$. For comparison with other experiments we used $\Gamma(K \rightarrow e\pi^0\nu)/\Gamma_{\text{all}} = 0.0482$ to calculate the values quoted here.

[48] $\cos\theta(e\gamma)$ between 0.6 and 0.9.

[49] Both ROMANO 71 values are for $\cos\theta(e\gamma)$ between 0.6 and 0.9. Second value is for comparison with second LJUNG 73 value. We use lowest $E(\gamma)$ cut for Summary Table value. See ROMANO 71 for E_γ dependence.

[50] First LJUNG 73 value is for $\cos\theta(e\gamma)$ <0.9, second value is for $\cos\theta(e\gamma)$ between 0.6 and 0.9 for comparison with ROMANO 71.

$\Gamma(\pi^0 e^+\nu_e\gamma(\text{SD}))/\Gamma_{\text{total}}$ Γ_{26}/Γ

Structure-dependent part.

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	CHG
<5.3	90	BOLOTOV 86B	CALO	−

$\Gamma(\pi^0\pi^0 e^+\nu_e\gamma)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<5	90	0	BARMIN 92	XEBC	+	E_γ > 10 MeV

$\Gamma(\pi^+\pi^+ e^-\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{28}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 9.0	95	0	SCHWEINB... 71	HLBC	+
< 6.9	95	0	ELY 69	HLBC	+
<20.	95		BIRGE 65	FBC	+

$\Gamma(\pi^+\pi^+e^-\overline{\nu}_e)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{28}/Γ_9

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
< 3	90	3	[51] BLOCH 76	SPEC

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
<130.	95	0	BOURQUIN 71	ASPK

[51] BLOCH 76 quotes 3.6×10^{-4} at CL = 95%, we convert.

$\Gamma(\pi^+\pi^+\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$ Γ_{29}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<3.0	95	0	BIRGE 65	FBC	+

$\Gamma(\pi^+e^+e^-)/\Gamma_{\text{total}}$ Γ_{30}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by combined first-order weak and electromagnetic interactions.

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
2.74±0.23 OUR AVERAGE						
2.75±0.23±0.13		500	[52] ALLIEGRO 92	SPEC	+	
2.7 ±0.5		41	[53] BLOCH 75	SPEC	+	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
< 17	90		CENCE 74	ASPK	+	Three track evts
< 2.7	90		CENCE 74	ASPK	+	Two track events
<320	90		BEIER 72	OSPK	±	
< 44	90		BISI 67	DBC	+	
< 8.8	90		CLINE 67B	FBC	+	
< 24.5	90	1	CAMERINI 64	FBC	+	

[52] ALLIEGRO 92 assumes a vector interaction with a form factor given by $\lambda = 0.105 \pm 0.035 \pm 0.015$ and a correlation coefficient of -0.82.

[53] BLOCH 75 assumes a vector interaction.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{31}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-8})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*
5.0±0.4±0.9		[54] ADLER 97C	B787	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-8})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*
< 23	90	ATIYA 89	B787	+
<240	90	BISI 67	DBC	+
<300	90	CAMERINI 65	FBC	+

[54] ADLER 97C gives systematic error 0.7×10^{-8} and theoretical uncertainty 0.6×10^{-8}, which we combine in quadrature to obtain our second error.

$\Gamma(\pi^+\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_{32}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
$\mathbf{0.42^{+0.97}_{-0.35}}$		1	ADLER 97	B787		

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
< 2.4	90		ADLER 96	B787		
< 7.5	90		ATIYA 93	B787	+	$T(\pi)$ 115–127 MeV
< 5.2	90		[55] ATIYA 93	B787	+	
< 17	90	0	ATIYA 93B	B787	+	$T(\pi)$ 60–100 MeV
< 34	90		ATIYA 90	B787	+	
< 140	90		ASANO 81B	CNTR	+	$T(\pi)$ 116–127 MeV
< 940	90		[56] CABLE 73	CNTR	+	$T(\pi)$ 60–105 MeV
< 560	90		[56] CABLE 73	CNTR	+	$T(\pi)$ 60–127 MeV
<57000	90	0	[57] LJUNG 73	HLBC	+	
< 1400	90		[56] KLEMS 71	OSPK	+	$T(\pi)$ 117–127 MeV

[55] Combining ATIYA 93 and ATIYA 93B results. Superseded by ADLER 96.

[56] KLEMS 71 and CABLE 73 assume π spectrum same as K_{e3} decay. Second CABLE 73 limit combines CABLE 73 and KLEMS 71 data for vector interaction.

[57] LJUNG 73 assumes vector interaction.

$\Gamma(\mu^-\nu e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{33}/Γ_9

Test of lepton family number conservation.

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<0.5	90	0	[58] DIAMANT-... 76	SPEC	+

[58] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio.

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ Γ_{34}/Γ

Forbidden by lepton family number conservation.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.004	90	0	[59] LYONS 81	HLBC	0	200 GeV K^+ narrow band ν beam

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.012	90		[59] COOPER 82	HLBC		Wideband ν beam

[59] COOPER 82 and LYONS 81 limits on ν_e observation are here interpreted as limits on lepton family number violation in the absence of mixing.

$\Gamma(\pi^+\mu^+e^-)/\Gamma_{\text{total}}$ Γ_{35}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
< 2.1	90	0	LEE 90	SPEC	+	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<11	90	0	CAMPAGNARI 88	SPEC	+	In LEE 90
<48	90	0	DIAMANT-... 76	SPEC	+	

$\Gamma(\pi^+\mu^-e^+)/\Gamma_{\text{total}}$ Γ_{36}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
< 7	90	0	[60] DIAMANT-... 76	SPEC	+

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<28	90		[60] BEIER 72	OSPK	±

[60] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^-\mu^+e^+)/\Gamma_{\text{total}}$ Γ_{37}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
< 7	90	0	[61] DIAMANT-... 76	SPEC	+

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<28	90		[61] BEIER 72	OSPK	±

[61] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^+\mu^-e^+)/\Gamma_{\text{total}}$ Γ_{36}/Γ

VALUE (units 10^{-8})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-8})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*
<1.4	90	BEIER 72	OSPK	±

$\Gamma(\pi^-e^+e^+)/\Gamma_{\text{total}}$ Γ_{38}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-5})	*DOCUMENT ID*	*TECN*	*CHG*

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-5})	*DOCUMENT ID*	*TECN*	*CHG*
<1.5	CHANG 68	HBC	−

$\Gamma(\pi^-e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{38}/Γ_9

Test of total lepton number conservation.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
<2.5	90	0	[62] DIAMANT-... 76	SPEC	+

[62] DIAMANT-BERGER 76 quotes this result times our 1975 BR ratio.

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$ Γ_{39}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*
<1.5	90	[63] LITTENBERG 92	HBC

[63] LITTENBERG 92 is from retroactive data analysis of CHANG 68 bubble chamber data.

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{40}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3.3	90	[64] COOPER 82	HLBC	Wideband ν beam

[64] COOPER 82 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton number violation in the absence of mixing.

$\Gamma(\pi^0e^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{41}/Γ

Forbidden by total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.003	90	[65] COOPER 82	HLBC	Wideband ν beam

[65] COOPER 82 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton number violation in the absence of mixing.

$\Gamma(\pi^+\gamma)/\Gamma_{\text{total}}$ Γ_{42}/Γ

Violates angular momentum conservation. Not listed in Summary Table.

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*
<1.4	90	ASANO 82	CNTR	+
<4.0	90	[66] KLEMS 71	OSPK	+

[66] Test of model of Selleri, Nuovo Cimento **60A** 291 (1969).

K^+ LONGITUDINAL POLARIZATION OF EMITTED μ^+

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<−0.990	90	[67] AOKI	94	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<−0.990	90	IMAZATO	92	SPEC	+	Repl. by AOKI 94
−0.970±0.047		[68] YAMANAKA	86	SPEC	+	
−1.0 ±0.1		[68] CUTTS	69	SPRK	+	
−0.96 ±0.12		[68] COOMBES	57	CNTR	+	

[67] AOKI 94 measures $\xi P_\mu = -0.9996 \pm 0.0030 \pm 0.0048$. The above limit is obtained by summing the statistical and systematic errors in quadrature, normalizing to the physically significant region ($|\xi P_\mu| < 1$) and assuming that ξ=1, its maximum value.

[68] Assumes ξ=1.

DALITZ PLOT PARAMETERS FOR $K \rightarrow 3\pi$ DECAYS

Revised 1994 by T.G. Trippe (LBNL).

The Dalitz plot distribution for $K^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}$, $K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}$, and $K^0_L \rightarrow \pi^+\pi^-\pi^0$ can be parameterized by a series expansion such as that introduced by Weinberg [1]. We use the form

$$\left|M\right|^2 \propto 1 + g\frac{(s_3 - s_0)}{am^2_{\pi^+}} + h\left[\frac{s_3 - s_0}{m^2_{\pi^+}}\right]^2 + j\,\frac{(s_2 - s_1)}{m^2_{\pi^+}} + k\left[\frac{s_2 - s_1}{m^2_{\pi^+}}\right]^2 + \cdots , \qquad (1)$$

where $m^2_{\pi^+}$ has been introduced to make the coefficients g, h, j, and k dimensionless, and

$$s_i = (P_K - P_i)^2 = (m_K - m_i)^2 - 2m_K T_i \ , \ i = 1,2,3,$$

$$s_0 = \frac{1}{3}\sum_i s_i = \frac{1}{3}(m^2_K + m^2_1 + m^2_2 + m^2_3)$$

Here the P_i are four-vectors, m_i and T_i are the mass and kinetic energy of the i^{th} pion, and the index 3 is used for the odd pion.

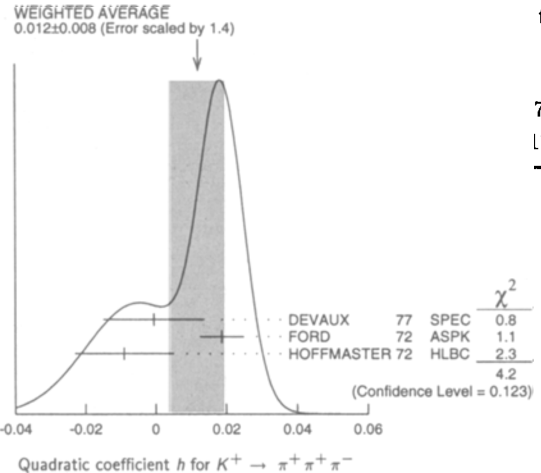
The coefficient g is a measure of the slope in the variable s_3 (or T_3) of the Dalitz plot, while h and k measure the quadratic dependence on s_3 and $(s_2 - s_1)$, respectively. The coefficient j is related to the asymmetry of the plot and must be zero if CP invariance holds. Note also that if CP is good, g, h, and k must be the same for $K^+ \rightarrow \pi^+\pi^+\pi^-$ as for $K^- \rightarrow \pi^-\pi^-\pi^+$.

Since different experiments use different forms for $\left|M\right|^2$, in order to compare the experiments we have converted to g, h, j, and k whatever coefficients have been measured. Where such conversions have been done, the measured coefficient a_y, a_t, a_u, or a_v is given in the comment at the right. For definitions of these coefficients, details of this conversion, and discussion of

this note [2].

7 (1960).

111B, 69 (1982).



Quadratic coefficient h for $K^+ \rightarrow \pi^+\pi^+\pi^-$

ENERGY DEPENDENCE OF $K^{\pm}$ DALITZ PLOT

$|\text{matrix element}|^2 = 1 + gu + hu^2 + kv^2$
where $u = (s_3 - s_0) / m^2_\pi$ and $v = (s_1 - s_2) / m^2_\pi$

LINEAR COEFFICIENT g_{τ^+} FOR $K^+ \rightarrow \pi^+\pi^+\pi^-$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \rightarrow 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the *Review* published in Physics Letters **111B** 70 (1982).

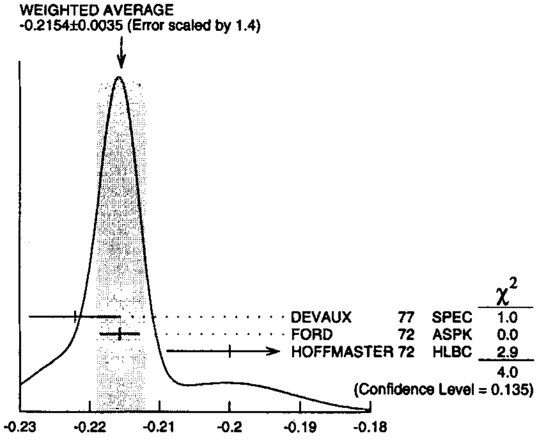
VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.2154±0.0035 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.				
−0.2221±0.0065	225k	DEVAUX	77	SPEC	+	a_y=.2814 ± .0082
−0.2157±0.0028	750k	FORD	72	ASPK	+	a_y=.2734 ± .0035
−0.200 ±0.009	39819	[69] HOFFMASTER	72	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.196 ±0.012	17898	[70] GRAUMAN	70	HLBC	+	a_y=0.228 ± 0.030
−0.218 ±0.016	9994	[71] BUTLER	68	HBC	+	a_y=0.277 ± 0.020
−0.22 ±0.024	5428	[71,72] ZINCHENKO	67	HBC	+	a_y=0.28 ± 0.03

[69] HOFFMASTER 72 includes GRAUMAN 70 data.

[70] Emulsion data added — all events included by HOFFMASTER 72.

[71] Experiments with large errors not included in average.

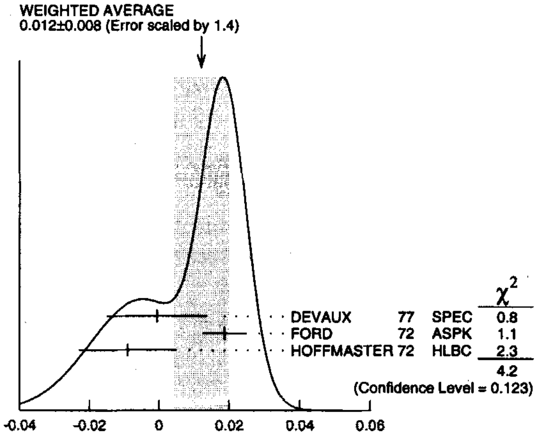
[72] Also includes DBC events.



Linear energy dependence for $K^+ \rightarrow \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT h FOR $K^+ \rightarrow \pi^+\pi^+\pi^-$

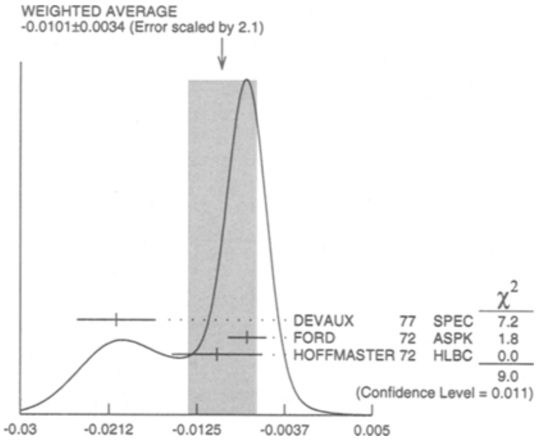
VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.012 ±0.008 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
−0.0006±0.0143	225k	DEVAUX	77	SPEC	+
0.0187±0.0062	750k	FORD	72	ASPK	+
−0.009 ±0.014	39819	HOFFMASTER	72	HLBC	+



Quadratic coefficient h for $K^+ \rightarrow \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT k FOR $K^+ \to \pi^+\pi^+\pi^-$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
−0.0101±0.0034 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.		
−0.0205±0.0039	225k	DEVAUX 77	SPEC	+
−0.0075±0.0019	750k	FORD 72	ASPK	+
−0.0105±0.0045	39819	HOFFMASTER 72	HLBC	+



Quadratic coefficient k for $K^+ \to \pi^+\pi^+\pi^-$

LINEAR COEFFICIENT g_{τ^-} FOR $K^- \to \pi^-\pi^-\pi^+$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the *Review* published in Physics Letters **111B** 70 (1982).

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.217 ±0.007 OUR AVERAGE		Error includes scale factor of 2.5.			
−0.2186±0.0028	750k	FORD 72	ASPK	−	a_y=.2770 ± .0035
−0.193 ±0.010	50919	MAST 69	HBC	−	a_y=0.244 ± 0.013
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.199 ±0.008	81k	[73] LUCAS 73	HBC	−	a_y=0.252 ± 0.011
−0.190 ±0.023	5778	[74,75] MOSCOSO 68	HBC	−	a_y=0.242 ± 0.029
−0.220 ±0.035	1347	[76] FERRO-LUZZI 61	HBC	−	a_y=0.28 ± 0.045

[73] Quadratic dependence is required by K^0_L experiments. For comparison we average only those $K^{\pm}$ experiments which quote quadratic fit values.
[74] Experiments with large errors not included in average.
[75] Also includes DBC events.
[76] No radiative corrections included.

QUADRATIC COEFFICIENT h FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.010 ±0.006 OUR AVERAGE				
0.0125±0.0062	750k	FORD 72	ASPK	−
−0.001 ±0.012	50919	MAST 69	HBC	−

QUADRATIC COEFFICIENT k FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
−0.0084±0.0019 OUR AVERAGE				
−0.0083±0.0019	750k	FORD 72	ASPK	−
−0.014 ±0.012	50919	MAST 69	HBC	−

$(g_{\tau^+} - g_{\tau^-}) / (g_{\tau^+} + g_{\tau^-})$ FOR $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$

A nonzero value for this quantity indicates *CP* violation.

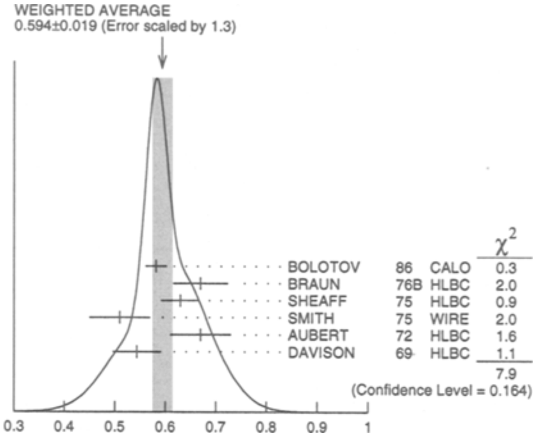
VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
−0.70±0.53	3.2M	FORD 70	ASPK

LINEAR COEFFICIENT g FOR $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

Unless otherwise stated, all experiments include terms quadratic in $(s_3 - s_0) / m^2_{\pi^+}$. See mini-review above.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.594±0.019 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
0.582±0.021	43k	BOLOTOV 86	CALO	−	
0.670±0.054	3263	BRAUN 76B	HLBC	+	
0.630±0.038	5635	SHEAFF 75	HLBC	+	
0.510±0.060	27k	SMITH 75	WIRE	+	
0.67 ±0.06	1365	AUBERT 72	HLBC	+	
0.544±0.048	4048	DAVISON 69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.806±0.220	4639	[77] BERTRAND 76	EMUL	+	
0.484±0.084	574	[78] LUCAS 73B	HBC	−	Dalitz pairs only
0.527±0.102	198	[77] PANDOULAS 70	EMUL	+	
0.586±0.098	1874	[78] BISI 65	HLBC	+	Also HBC
0.48 ±0.04	1792	[78] KALMUS 64	HLBC	+	

[77] Experiments with large errors not included in average.
[78] Authors give linear fit only.



Linear energy dependence for $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

QUADRATIC COEFFICIENT h FOR $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

See mini-review above.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.035±0.015 OUR AVERAGE					
0.037±0.024	43k	BOLOTOV 86	CALO	−	
0.152±0.082	3263	BRAUN 76B	HLBC	+	
0.041±0.030	5635	SHEAFF 75	HLBC	+	
0.009±0.040	27k	SMITH 75	WIRE	+	
−0.01 ±0.08	1365	AUBERT 72	HLBC	+	
0.026±0.050	4048	DAVISON 69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.164±0.121	4639	[79] BERTRAND 76	EMUL	+	
0.018±0.124	198	[79] PANDOULAS 70	EMUL	+	

[79] Experiments with large errors not included in average.

$K^{\pm}_{\ell 3}$ AND $K^0_{\ell 3}$ FORM FACTORS

Written by T.G. Trippe (LBNL).

Assuming that only the vector current contributes to $K \to \pi\ell\nu$ decays, we write the matrix element as

$$M \propto f_+(t)\left[(P_K + P_\pi)_\mu \bar{\ell}\gamma_\mu(1+\gamma_5)\nu\right] + f_-(t)\left[m_\ell \bar{\ell}(1+\gamma_5)\nu\right] , \quad (1)$$

where P_K and P_π are the four-momenta of the K and π mesons, m_ℓ is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. If time-reversal invariance holds, f_+ and f_- are relatively real. $K_{\mu 3}$ experiments measure f_+ and f_-, while K_{e3} experiments are sensitive only to f_+ because the small electron mass makes the f_- term negligible.

(a) $K_{\mu 3}$ *experiments.* Analyses of $K_{\mu 3}$ data frequently assume a linear dependence of f_+ and f_- on t, *i.e.*,

$$f_\pm(t) = f_\pm(0)\left[1 + \lambda_\pm(t/m_\pi^2)\right] \quad (2)$$

Most $K_{\mu 3}$ data are adequately described by Eq. (2) for f_+ and a constant f_- (*i.e.*, $\lambda_- = 0$). There are two equivalent parametrizations commonly used in these analyses:

(1) $\lambda_+, \xi(0)$ *parametrization.* Analyses of $K_{\mu 3}$ data often introduce the ratio of the two form factors

$$\xi(t) = f_-(t)/f_+(t) .$$

The $K_{\mu 3}$ decay distribution is then described by the two parameters λ_+ and $\xi(0)$ (assuming time reversal invariance and $\lambda_- = 0$). These parameters can be determined by three different methods:

Method A. By studying the Dalitz plot or the pion spectrum of $K_{\mu 3}$ decay. The Dalitz plot density is (see, *e.g.*, Chounet *et al.* [1]):

$$\rho(E_\pi, E_\mu) \propto f_+^2(t)\left[A + B\xi(t) + C\xi(t)^2\right] ,$$

where

$$\begin{aligned} A &= m_K\left(2E_\mu E_\nu - m_K E'_\pi\right) + m_\mu^2\left(\frac{1}{4}E'_\pi - E_\nu\right) , \\ B &= m_\mu^2\left(E_\nu - \frac{1}{2}E'_\pi\right) , \\ C &= \frac{1}{4}m_\mu^2 E'_\pi , \\ E'_\pi &= E_\pi^{\max} - E_\pi = \left(m_K^2 + m_\pi^2 - m_\mu^2\right)/2m_K - E_\pi . \end{aligned}$$

Here E_π, E_μ, and E_ν are, respectively, the pion, muon, and neutrino energies in the kaon center of mass. The density ρ is fit to the data to determine the values of $\lambda_+, \xi(0)$, and their correlation.

Method B. By measuring the $K_{\mu 3}/K_{e3}$ branching ratio and comparing it with the theoretical ratio (see, *e.g.*, Fearing *et al.* [2]) as given in terms of λ_+ and $\xi(0)$, assuming μ-e universality:

$$\begin{aligned} \Gamma(K_{\mu 3}^{\pm})/\Gamma(K_{e3}^{\pm}) &= 0.6457 + 1.4115\lambda_+ + 0.1264\xi(0) \\ &\quad + 0.0192\xi(0)^2 + 0.0080\lambda_+\xi(0) , \\ \Gamma(K_{\mu 3}^{0})/\Gamma(K_{e3}^{0}) &= 0.6452 + 1.3162\lambda_+ + 0.1264\xi(0) \\ &\quad + 0.0186\xi(0)^2 + 0.0064\lambda_+\xi(0) . \end{aligned}$$

This cannot determine λ_+ and $\xi(0)$ simultaneously but simply fixes a relationship between them.

Method C. By measuring the muon polarization in $K_{\mu 3}$ decay. In the rest frame of the K, the μ is expected to be polarized in the direction $\mathbf{A}$ with $\mathbf{P} = \mathbf{A}/\left|\mathbf{A}\right|$, where $\mathbf{A}$ is given (Cabibbo and Maksymowicz [3]) by

$$\begin{aligned} \mathbf{A} &= a_1(\xi)\mathbf{p}_\mu \\ &\quad - a_2(\xi)\left[\frac{\mathbf{p}_\mu}{m_\mu}\left(m_K - E_\pi + \frac{\mathbf{p}_\pi \cdot \mathbf{p}_\mu}{\left|\mathbf{p}_\mu\right|^2}(E_\mu - m_\mu)\right) + \mathbf{p}_\pi\right] \\ &\quad + m_K \mathrm{Im}\xi(t)(\mathbf{p}_\pi \times \mathbf{p}_\mu) . \end{aligned}$$

If time-reversal invariance holds, ξ is real, and thus there is no polarization perpendicular to the K-decay plane. Polarization experiments measure the weighted average of $\xi(t)$ over the t range of the experiment, where the weighting accounts for the variation with t of the sensitivity to $\xi(t)$.

(2) λ_+, λ_0 parametrization. Most of the more recent $K_{\mu 3}$ analyses have parameterized in terms of the form factors f_+ and f_0 which are associated with vector and scalar exchange, respectively, to the lepton pair. f_0 is related to f_+ and f_- by

$$f_0(t) = f_+(t) + \left[t/(m_K^2 - m_\pi^2)\right] f_-(t) .$$

Here $f_0(0)$ must equal $f_+(0)$ unless $f_-(t)$ diverges at $t = 0$. The earlier assumption that f_+ is linear in t and f_- is constant leads to f_0 linear in t:

$$f_0(t) = f_0(0)\left[1 + \lambda_0(t/m_\pi^2)\right] .$$

With the assumption that $f_0(0) = f_+(0)$, the two parametrizations, $(\lambda_+, \xi(0))$ and (λ_+, λ_0) are equivalent as long as correlation information is retained. (λ_+, λ_0) correlations tend to be less strong than $(\lambda_+, \xi(0))$ correlations.

The experimental results for $\xi(0)$ and its correlation with λ_+ are listed in the $K^{\pm}$ and K_L^0 sections of the Particle Listings in section ξ_{A}, ξ_{B}, or ξ_{C} depending on whether method A, B, or C discussed above was used. The corresponding values of λ_+ are also listed.

Because recent experiments tend to use the (λ_+, λ_0) parametrization, we include a subsection for λ_0 results. Wherever possible we have converted $\xi(0)$ results into λ_0 results and vice versa.

See the 1982 version of this note [4] for additional discussion of the $K_{\mu 3}^0$ parameters, correlations, and conversion between parametrizations, and also for a comparison of the experimental results.

(b) K_{e3} experiments. Analysis of K_{e3} data is simpler than that of $K_{\mu 3}$ because the second term of the matrix element assuming a pure vector current [Eq. (1) above] can be neglected. Here f_+ is usually assumed to be linear in t, and the linear coefficient λ_+ of Eq. (2) is determined.

If we remove the assumption of a pure vector current, then the matrix element for the decay, in addition to the terms in Eq. (2), would contain

$$\begin{aligned} &+2m_K f_S \bar{\ell}(1 + \gamma_5)\nu \\ &\qquad +(2f_T/m_K)(P_K)_\lambda(P_\pi)_\mu \bar{\ell}\sigma_{\lambda\mu}(1 + \gamma_5)\nu , \end{aligned}$$

where f_S is the scalar form factor, and f_T is the tensor form factor. In the case of the K_{e3} decays where the f_- term can be neglected, experiments have yielded limits on $|f_S/f_+|$ and $|f_T/f_+|$.

References

1. L.M. Chounet, J.M. Gaillard, and M.K. Gaillard, Phys. Reports **4C**, 199 (1972).
2. H.W. Fearing, E. Fischbach, and J. Smith, Phys. Rev. **D2**, 542 (1970).
3. N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964).
4. Particle Data Group, Phys. Lett. **111B**, 73 (1982).

$K^{\pm}_{\ell 3}$ FORM FACTORS

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.
f_S and f_T refer to the scalar and tensor term.
$f_0 = f_+ + f_- t/(m^2_K - m^2_\pi)$.
λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.
λ_+ refers to the $K^{\pm}_{\mu 3}$ value except in the $K^{\pm}_{e3}$ sections.
$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K^{\pm}_{\mu 3}$.
$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K^{\pm}_{\mu 3}$.
t = momentum transfer to the π in units of m^2_π.
DP = Dalitz plot analysis.
PI = π spectrum analysis.
MU = μ spectrum analysis.
POL= μ polarization analysis.
BR = $K^{\pm}_{\mu 3}/K^{\pm}_{e3}$ branching ratio analysis.
E = positron or electron spectrum analysis.
RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^{\pm}_{e3}$ DECAY)

For radiative correction of $K^{\pm}_{e3}$ Dalitz plot, see GINSBERG 67 and BECHERRAWY 70.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.0286±0.0022 OUR AVERAGE					
0.0284±0.0027±0.0020	32k	[80] AKIMENKO 91	SPEC		PI, no RC
0.029 ±0.004	62k	[81] BOLOTOV 88	SPEC		PI, no RC
0.027 ±0.008		[82] BRAUN 73B	HLBC	+	DP, no RC
0.029 ±0.011	4017	CHIANG 72	OSPK	+	DP, RC negligible
0.027 ±0.010	2707	STEINER 71	HLBC	+	DP, uses RC
0.045 ±0.015	1458	BOTTERILL 70	OSPK		PI, uses RC
0.08 ±0.04	960	BOTTERILL 68C	ASPK	+	e^+, uses RC
$-0.02^{+0.08}_{-0.12}$	90	EISLER 68	HLBC	+	PI, uses RC
$0.045^{+0.017}_{-0.018}$	854	BELLOTTI 67B	FBC	+	DP, uses RC
+0.016 ±0.016	1393	IMLAY 67	OSPK	+	DP, no RC
$+0.028^{+0.013}_{-0.014}$	515	KALMUS 67	FBC	+	e^+, PI, no RC
−0.04 ±0.05	230	BORREANI 64	HBC	+	e^+, no RC
−0.010 ±0.029	407	JENSEN 64	XEBC	+	PI, no RC
+0.036 ±0.045	217	BROWN 62B	XEBC	+	PI, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.025 ±0.007		[83] BRAUN 74	HLBC	+	$K_{\mu 3}/K_{e3}$ vs. t

[80] AKIMENKO 91 state that radiative corrections would raise λ_+ by 0.0013.

[81] BOLOTOV 88 state radiative corrections of GINSBERG 67 would raise λ_+ by 0.002.

[82] BRAUN 73B states that radiative corrections of GINSBERG 67 would lower λ^e_+ by 0.002 but that radiative corrections of BECHERRAWY 70 disagrees and would raise λ^e_+ by 0.005.

[83] BRAUN 74 is a combined $K_{\mu 3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu 3}$) and BRAUN 73B (K_{e3}) form factor results.

$\xi_A = f_-/f_+$ (determined from $K^{\pm}_{\mu 3}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	*$d\xi(0)/d\lambda_+$*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.33±0.14 OUR EVALUATION			Error includes scale factor of 1.6. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.27±0.25	−17	3973	WHITMAN 80	SPEC	+	DP
−0.8 ±0.8	−20	490	[84] ARNOLD 74	HLBC	+	DP
−0.57±0.24	−9	6527	[85] MERLAN 74	ASPK	+	DP
−0.36±0.40	−19	1897	[86] BRAUN 73C	HLBC	+	DP
−0.62±0.28	−12	4025	[87] ANKENBRA... 72	ASPK	+	PI
+0.45±0.28	−15	3480	[88] CHIANG 72	OSPK	+	DP
−1.1 ±0.56	−29	3240	[89] HAIDT 71	HLBC	+	DP
−0.5 ±0.8	−26	2041	[90] KIJEWSKI 69	OSPK	+	PI
+0.72±0.93	−17	444	CALLAHAN 66B	FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.5 ±0.9	none	78	EISLER 68	HLBC	+	PI, $\lambda_+=0$
$0.0^{+1.1}_{-0.9}$		2648	[91] CALLAHAN 66B	FBC	+	μ, $\lambda_+=0$
+0.7 ±0.5		87	GIACOMELLI 64	EMUL	+	MU+BR,$\lambda_+=0$
−0.08±0.7			[92] JENSEN 64	XEBC	+	DP+BR
+1.8 ±0.6		76	BROWN 62B	XEBC	+	DP+BR, $\lambda_+=0$

[84] ARNOLD 74 figure 4 was used to obtain ξ_A and $d\xi(0)/d\lambda_+$.

[85] MERLAN 74 figure 5 was used to obtain $d\xi(0)/d\lambda_+$.

[86] BRAUN 73C gives $\xi(t) = -0.34 \pm 0.20$, $d\xi(t)/d\lambda_+ = -14$ for $\lambda_+ = 0.027$, $t = 6.6$. We calculate above $\xi(0)$ and $d\xi(0)/d\lambda_+$ for their $\lambda_+ = 0.025 \pm 0.017$.

[87] ANKENBRANDT 72 figure 3 was used to obtain $d\xi(0)/d\lambda_+$.

[88] CHIANG 72 figure 10 was used to obtain $d\xi(0)/d\lambda_+$. Fit had $\lambda_- = \lambda_+$ but would not change for $\lambda_- = 0$. L.Pondrom, (private communication 74).

[89] HAIDT 71 table 8 (Dalitz plot analysis) gives $d\xi(0)/d\lambda_+ = (-1.1+0.5)/(0.050-0.029) = -29$, error raised from 0.50 to agree with $d\xi(0) = 0.20$ for fixed λ_+.

[90] KIJEWSKI 69 figure 17 was used to obtain $d\xi(0)/d\lambda_+$ and errors.

[91] CALLAHAN 66 table 1 (π analysis) gives $d\xi(0)/d\lambda_+ = (0.72-0.05)/(0-0.04) = -17$, error raised from 0.80 to agree with $d\xi(0) = 0.37$ for fixed λ_+. t unknown.

[92] JENSEN 64 gives $\lambda^\mu_+ = \lambda^e_+ = -0.020 \pm 0.027$. $d\xi(0)/d\lambda_+$ unknown. Includes SHAKLEE 64 $\xi_B(K_{\mu 3}/K_{e3})$.

$\xi_B = f_-/f_+$ (determined from $K^{\pm}_{\mu 3}/K^{\pm}_{e3}$)

The $K^{\pm}_{\mu 3}/K^{\pm}_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_B values. Instead they are obtained directly from the fitted $K^{\pm}_{\mu 3}/K^{\pm}_{e3}$ ratio $\Gamma(\pi^0 \mu^+ \nu_\mu)/\Gamma(\pi^0 e^+ \nu_e)$, with the exception of HEINTZE 77. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.33±0.14 OUR EVALUATION		Error includes scale factor of 1.6. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.12±0.12	55k	[93] HEINTZE 77	CNTR	+	$\lambda_+=0.029$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0 ±0.15	5825	CHIANG 72	OSPK	+	$\lambda_+=0.03$, fig.10
−0.81±0.27	1505	[94] HAIDT 71	HLBC	+	$\lambda_+=0.028$, fig.8
−0.35±0.22		[95] BOTTERILL 70	OSPK	+	$\lambda_+=0.045\pm0.015$
+0.91±0.82		ZELLER 69	ASPK	+	$\lambda_+=0.023$
−0.08±0.15	5601	[95] BOTTERILL 68B	ASPK	+	$\lambda_+=0.023\pm0.008$
−0.60±0.20	1398	[94] EICHTEN 68	HLBC	+	See note
+1.0 ±0.6	986	GARLAND 68	OSPK	+	$\lambda_+=0$
+0.75±0.50	306	AUERBACH 67	OSPK	+	$\lambda_+=0$
+0.4 ±0.4	636	CALLAHAN 66B	FBC	+	$\lambda_+=0$
+0.6 ±0.5		BISI 65B	HBC	+	$\lambda_+=0$
+0.8 ±0.6	500	CUTTS 65	OSPK	+	$\lambda_+=0$
$-0.17^{+0.75}_{-0.99}$		SHAKLEE 64	XEBC	+	$\lambda_+=0$

[93] Calculated by us from λ_0 and λ_+ given below.

[94] EICHTEN 68 has $\lambda_+ = 0.023 \pm 0.008$, $t = 4$, independent of λ_-. Replaced by HAIDT 71.

[95] BOTTERILL 70 is re-evaluation of BOTTERILL 68B with different λ_+.

$\xi_C = f_-/f_+$ (determined from μ polarization in $K^{\pm}_{\mu 3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+=0$. $d\xi/d\lambda = \xi t$. For radiative correction to muon polarization in $K^{\pm}_{\mu 3}$, see GINSBERG 71. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.33±0.14 OUR EVALUATION		Error includes scale factor of 1.6. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.25±1.20	1585	[96] BRAUN 75	HLBC	+	POL, t=4.2
−0.95±0.3	3133	[97] CUTTS 69	OSPK	+	Total pol. t=4.0
−1.0 ±0.3	6000	[98] BETTELS 68	HLBC	+	Total pol. t=4.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.64±0.27	40k	[99] MERLAN 74	ASPK	+	POL, $d\xi(0)/d\lambda_+ = +1.7$
−1.4 ±1.8	397	[100] CALLAHAN 66B	FBC	+	Total pol.
$-0.7^{+0.9}_{-3.3}$	2950	[100] CALLAHAN 66B	FBC	+	Long. pol.
$+1.2^{+2.4}_{-1.8}$	2100	[100] BORREANI 65	HLBC	+	Polarization
−4.0 to +1.7	500	[100] CUTTS 65	OSPK	+	Long. pol.

[96] BRAUN 75 $d\xi(0)/d\lambda_+ = \xi t = -0.25\times4.2 = -1.0$.

[97] CUTTS 69 $t = 4.0$ was calculated from figure 8. $d\xi(0)/d\lambda_+ = \xi t = -0.95\times4 = -3.8$.

[98] BETTELS 68 $d\xi(0)/d\lambda_+ = \xi t = -1.0\times4.9 = -4.9$.

[99] MERLAN 74 polarization result (figure 5) not possible. See discussion of polarization experiments in note on "$K_{\ell 3}$ Form Factors" in the 1982 edition of this *Review* [Physics Letters **111B** (1982)].

[100] t value not given.

Im(ξ) in $K^{\pm}_{\mu 3}$ DECAY (from transverse μ pol.)

Test of T reversal invariance.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.017±0.025 OUR AVERAGE					
−0.016±0.025	20M	CAMPBELL 81	CNTR	+	Pol.
$-0.3^{+0.3}_{-0.4}$	3133	CUTTS 69	OSPK	+	Total pol. fig.7
−0.1 ±0.3	6000	BETTELS 68	HLBC	+	Total pol.
0.0 ±1.0	2648	CALLAHAN 66B	FBC	+	MU
+1.6 ±1.3	397	CALLAHAN 66B	FBC	+	Total pol.
$0.5^{+1.4}_{-0.5}$	2950	CALLAHAN 66B	FBC	+	Long. pol.
• • • We do not use the following data for averages, fits, limits, etc. • • •					

-0.010 ± 0.019	32M	[101] BLATT	83	CNTR	Polarization

[101] Combined result of MORSE 80 ($K^0_{\mu3}$) and CAMPBELL 81 ($K^+_{\mu3}$).

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^\pm_{\mu3}$ DECAY)

See also the corresponding entries and footnotes in sections ξ_A, ξ_C, and λ_0. For radiative correction of $K^\pm_{\mu3}$ Dalitz plot, see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.032 ± 0.008 OUR EVALUATION	Error includes scale factor of 1.6. From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).				
0.029 ± 0.024	3000	ARTEMOV	97	SPEC	$-$	DP
$+0.050\pm0.013$	3973	WHITMAN	80	SPEC	+	DP
0.025 ± 0.030	490	ARNOLD	74	HLBC	+	DP
0.027 ± 0.019	6527	MERLAN	74	ASPK	+	DP
0.025 ± 0.017	1897	BRAUN	73C	HLBC	+	DP
0.024 ± 0.019	4025	[102] ANKENBRA...	72	ASPK	+	PI
-0.006 ± 0.015	3480	CHIANG	72	OSPK	+	DP
0.050 ± 0.018	3240	HAIDT	71	HLBC	+	DP
0.009 ± 0.026	2041	KIJEWSKI	69	OSPK	+	PI
$0.0\ \ \pm0.05$	444	CALLAHAN	66B	FBC	+	PI

[102] ANKENBRANDT 72 λ_+ from figure 3 to match $d\xi(0)/d\lambda_+$. Text gives 0.024 ± 0.022.

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^\pm_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ^μ_+ and $d\xi/d\lambda$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.006 ± 0.007 OUR EVALUATION	Error includes scale factor of 1.6. Correlation is $d\lambda_0/d\lambda_+=-0.16$. From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).					
$+0.062\pm0.024$	0.0	3000	[103] ARTEMOV	97	SPEC	$-$	DP
$+0.029\pm0.011$	-0.37	3973	WHITMAN	80	SPEC	+	DP
$+0.019\pm0.010$	$+0.03$	55k	[104] HEINTZE	77	SPEC	+	BR
$+0.008\pm0.097$	$+0.92$	1585	[105] BRAUN	75	HLBC	+	POL
-0.040 ± 0.040	-0.62	490	ARNOLD	74	HLBC	+	DP
-0.019 ± 0.015	$+0.27$	6527	[106] MERLAN	74	ASPK	+	DP
-0.008 ± 0.020	-0.53	1897	[107] BRAUN	73C	HLBC	+	DP
-0.026 ± 0.013	$+0.03$	4025	[108] ANKENBRA...	72	ASPK	+	PI
$+0.030\pm0.014$	-0.21	3480	[108] CHIANG	72	OSPK	+	DP
-0.039 ± 0.029	-1.34	3240	[108] HAIDT	71	HLBC	+	DP
-0.056 ± 0.024	$+0.69$	3133	[105] CUTTS	69	OSPK	+	POL
-0.031 ± 0.045	-1.10	2041	[108] KIJEWSKI	69	OSPK	+	PI
-0.063 ± 0.024	$+0.60$	6000	[105] BETTELS	68	HLBC	+	POL
$+0.058\pm0.036$	-0.37	444	[108] CALLAHAN	66B	FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
-0.017 ± 0.011			[109] BRAUN	74	HLBC	+	$K_{\mu3}/K_{e3}$ vs. t

[103] ARTEMOV 97 does not give $d\lambda_0/d\lambda_+$ so we take it to be zero.

[104] HEINTZE 77 uses $\lambda_+=0.029\pm0.003$. $d\lambda_0/d\lambda_+$ estimated by us.

[105] λ_0 value is for $\lambda_+=0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[106] MERLAN 74 λ_0 and $d\lambda_0/d\lambda_+$ were calculated by us from ξ_A, λ^μ_+, and $d\xi(0)/d\lambda_+$. Their figure 6 gives $\lambda_0=-0.025\pm0.012$ and no $d\lambda_0/d\lambda_+$.

[107] This value and error are taken from BRAUN 75 but correspond to the BRAUN 73C λ^μ_+ result. $d\lambda_0/d\lambda_+$ is from BRAUN 73C $d\xi(0)/d\lambda_+$ in ξ_A above.

[108] λ_0 calculated by us from $\xi(0)$, λ^μ_+, and $d\xi(0)/d\lambda_+$.

[109] BRAUN 74 is a combined $K_{\mu3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu3}$) and BRAUN 73B (K_{e3}) form factor results.

$|f_S/f_+|$ FOR $K^\pm_{e3}$ DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.084 ± 0.023 OUR AVERAGE	Error includes scale factor of 1.2.					
$0.070\pm0.016\pm0.016$		32k	AKIMENKO	91	SPEC		λ_+, f_S, f_T, ϕ fit
$0.00\ \pm0.10$		2827	BRAUN	75	HLBC	+	
$0.14\ ^{+0.03}_{-0.04}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.13	90	4017	CHIANG	72	OSPK	+	
<0.23	90		BOTTERILL	68C	ASPK		
<0.18	90		BELLOTTI	67B	HLBC		
<0.30	95		KALMUS	67	HLBC	+	

$|f_T/f_+|$ FOR $K^\pm_{e3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.38 ± 0.11 OUR AVERAGE	Error includes scale factor of 1.1.					
$0.53^{+0.09}_{-0.10}\pm0.10$		32k	AKIMENKO	91	SPEC		λ_+, f_S, f_T, ϕ fit
0.07 ± 0.37		2827	BRAUN	75	HLBC	+	
$0.24^{+0.16}_{-0.14}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.75	90	4017	CHIANG	72	OSPK	+	
<0.58	90		BOTTERILL	68C	ASPK		
<0.58	90		BELLOTTI	67B	HLBC		
<1.1	95		KALMUS	67	HLBC	+	

f_T/f_+ FOR $K^\pm_{\mu3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	EVTS	DOCUMENT ID	TECN
0.02 ± 0.12	1585	BRAUN	75	HLBC

DECAY FORM FACTORS FOR $K^\pm \to \pi^+\pi^- e^\pm\nu_e$

Given in ROSSELET 77, BEIER 73, and BASILE 71C.

DECAY FORM FACTOR FOR $K^\pm \to \pi^0\pi^0 e^\pm\nu$

Given in BOLOTOV 86B and BARMIN 88B.

$K^\pm \to \ell^\pm\nu\gamma$ FORM FACTORS

For definitions of the axial-vector F_A and vector F_V form factor, see the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section. In the kaon literature, often different definitions $a_K = F_A/m_K$ and $v_K = F_V/m_K$ are used.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \to e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.148 ± 0.010 OUR AVERAGE				
0.147 ± 0.011	51	[110] HEINTZE	79	SPEC	$K\to e\nu\gamma$
$0.150^{+0.018}_{-0.023}$	56	[111] HEARD	75	SPEC	$K\to e\nu\gamma$

[110] HEINTZE 79 quotes absolute value of $\lvert F_A+F_V\rvert\sin\theta_c$. We use $\sin\theta_c=V_{us}=0.2205$.

[111] HEARD 75 quotes absolute value of $\lvert F_A+F_V\rvert\sin\theta_c$. We use $\sin\theta_c=V_{us}=0.2205$.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \to \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.23	90	[112] AKIBA	85	SPEC	$K\to\mu\nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-1.2 to 1.1	90	DEMIDOV	90	XEBC	$K\to\mu\nu\gamma$

[112] AKIBA 85 quotes absolute value.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \to e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<0.49	90	[113] HEINTZE	79	SPEC	$K\to e\nu\gamma$

[113] HEINTZE 79 quotes $\lvert F_A-F_V\rvert<\sqrt{11}\,\lvert F_A+F_V\rvert$.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \to \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
-2.2 to 0.3 OUR EVALUATION				
-2.2 to 0.6	90	DEMIDOV	90	XEBC	$K\to\mu\nu\gamma$
-2.5 to 0.3	90	AKIBA	85	SPEC	$K\to\mu\nu\gamma$

$K^\pm$ REFERENCES

ADLER 97 PRL 79 2204 S. Adler+ (BNL 787 Collab.)
ADLER 97C PRL 79 4756 S. Adler+ (BNL 787 Collab.)
ARTEMOV 97 PAN 60 218 V.M. Artemov+ (JINR)
Translated from YAF 60 277.
KITCHING 97 PRL 79 4079 P. Kitching+ (BNL 787 Collab.)
ADLER 96 PRL 76 1421 +Atiya, Chiang, Frank, Haggerty, Kycia+ (BNL 787 Collab.)
KOPTEV 95 JETPL 61 877 +Mikirtych'yants, Shcherbakov+ (PNPI)
Translated from ZETFP 61 865.
AOKI 94 PR D50 69 +Yamazaki, Imazato, Kawashima+ (INUS, KEK, TOKMS)
ATIYA 93 PRL 70 2521 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
Also 93C PRL 71 305 (erratum) Atiya, Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
ATIYA 93B PR D48 R1 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
BIJNENS 93 NP B396 81 +Ecker, Gasser (CERN, BERN)
ALLIEGRO 92 PRL 68 278 +Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
BARMIN 92 SJNP 55 547 +Barylov, Chernukha, Davidenko+ (ITEP)
Translated from YAF 55 976.
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
IVANOV 92 THESIS (PNPI)
LITTENBERG 92 PRL 68 443 +Shrock (BNL, STON)
USHER 92 PR D45 3961 +Fero, Gee, Graf, Mandelkern, Schultz, Schultz (UCI)
AKIMENKO 91 PL B259 225 +Beloussov+ (SERP, JINR, TBIL, CMNS, SOFU, KOSI)
BARMIN 91 SJNP 53 606 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 53 981.
DENISOV 91 JETPL 54 558 +Zhelamkov, Ivanov, Lapina, Levchenko, Malakhov+ (PNPI)
Translated from ZETFP 54 557.
Also 92 THESIS Ivanov (PNPI)
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
DEMIDOV 90 SJNP 52 1006 +Dobrokhotov, Lyublev, Nikitenko+ (ITEP)
Translated from YAF 52 1595.
LEE 90 PRL 64 165 +Alliegro, Campagnari+ (BNL, FNAL, VILL, WASH, YALE)
ATIYA 89 PRL 63 2177 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
BARMIN 89 SJNP 50 421 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 50 679.
BARMIN 88 SJNP 47 643 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 47 1011.
BARMIN 88B SJNP 48 1032 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 48 1719.
BOLOTOV 88 JETPL 47 7 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (ASCI)
Translated from ZETFP 47 8.

CAMPAGNARI 88 PRL 61 2062 +Alllegro, Chaloupka+ (BNL, FNAL, PSI, WASH, YALE)
GALL 88 PRL 60 186 +Austin+ (BOST, MIT, WILL, CIT, CMU, WYOM)
BARMIN 87 SJNP 45 62 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 45 97.
BOLOTOV 87 SJNP 45 1023 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (INRM)
Translated from YAF 45 1652.
BOLOTOV 86 SJNP 44 73 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 117.
BOLOTOV 86B SJNP 44 68 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 108.
YAMANAKA 86 PR D34 85 +Hayano, Taniguchi, Ishikawa+ (KEK, TOKY)
Also 84 PRL 52 329 Hayano, Yamanaka, Taniguchi+ (TOKY, KEK)
AKIBA 85 PR D32 2911 +Ishikawa, Iwasaki+ (TOKY, TINT, TSUK, KEK)
BOLOTOV 85 JETPL 42 481 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from ZETFP 42 390.
BLATT 83 PR D27 1056 +Adair, Black, Campbell+ (YALE, BNL)
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
PDG 82B PL 111B 70 Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
CAMPBELL 81 PRL 47 1032 +Black, Blatt, Kasha, Schmidt+ (YALE, BNL)
Also 83 PR D27 1056 Blatt, Adair, Black, Campbell+ (YALE, BNL)
LUM 81 PR D23 2522 +Wiegand, Kessler, Deslattes, Seki+ (LBL, NBS+)
LYONS 81 ZPHY C10 215 +Albajar, Myatt (OXF)
MORSE 80 PR D21 1750 +Leipuner, Larsen, Schmidt, Blatt+ (BNL, YALE)
WHITMAN 80 PR D21 652 +Abrams, Carroll, Kycia, Li+ (ILLC, BNL, ILL)
BARKOV 79 NP B148 53 +Vasserman, Zolotorev, Krupin+ (NOVO, KIAE)
HEINTZE 79 NP B149 365 +Heinzelmann, Igo-Kemenes+ (HEIDP, CERN)
ABRAMS 77 PR D15 22 +Carroll, Kycia, Li, Michael, Mockett+ (BNL)
DEVAUX 77 NP B126 11 +Bloch, Diamant-Berger, Maillard+ (SACL, GEVA)
HEINTZE 77 PL 70B 482 +Heinzelmann, Igo-Kemenes+ (HEIDP, CERN)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
BERTRAND 76 NP B114 387 +Sacton+ (BRUX, KIDR, DUUC, LOUC, WARS)
BLOCH 76 PL 60B 393 +Bunce, Devaux, Diamant-Berger+ (GEVA, SACL)
BRAUN 76B LNC 17 521 +Martyn, Erriquez+ (AACH3, BARI, BELG, CERN)
DIAMANT-... 76 PL 62B 485 Diamant-Berger, Bloch, Devaux+ (SACL, GEVA)
HEINTZE 76 PL 60B 302 +Heinzelmann, Igo-Kemenes, Mundhenke+ (HEIDP)
SMITH 76 NP B109 173 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
WEISSENBE... 76 NP B115 55 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
BLOCH 75 PL 56B 201 +Brehin, Bunce, Devaux+ (SACL, GEVA)
BRAUN 75 NP B89 210 +Cornelssen+ (AACH3, BARI, BRUX, CERN)
CHENG 75 NP A254 381 +Asano, Chen, Dugan, Hu, Wu+ (COLU, YALE)
HEARD 75 PL 55B 324 +Heintze, Heinzelmann+ (CERN, HEIDH)
HEARD 75B PL 55B 327 +Heintze, Heinzelmann+ (CERN, HEIDH)
SHEAFF 75 PR D12 2570 (WISC)
SMITH 75 NP B91 45 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ARNOLD 74 PR D9 1221 +Roe, Sinclair (MICH)
BRAUN 74 PL 51B 393 +Cornelssen, Martyn+ (AACH3, BARI, BRUX, CERN)
CENCE 74 PR D10 776 +Harris, Jones, Morgado+ (HAWA, LBL, WISC)
Also 73 Thesis unpub. Clarke (WISC)
KUNSELMAN 74 PR C9 2469 (WYOM)
MERLAN 74 PR D9 107 +Kasha, Wanderer, Adair+ (YALE, BNL, LASL)
WEISSENBE... 74 PL 48B 474 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
ABRAMS 73B PRL 30 500 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
BACKENSTO... 73 PL 43B 431 Backenstoss+ (CERN, KARLK, KARLE, HEID, STOH)
BEIER 73 PRL 30 399 +Buchholz, Mann, Parker, Roberts (PENN)
BRAUN 73B PL 47B 185 +Cornelssen (AACH3, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH3, BARI, BRUX, CERN)
BRAUN 73C PL 47B 182 +Cornelssen (AACH3, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH3, BARI, BRUX, CERN)
CABLE 73 PR D8 3807 +Hildebrand, Pang, Stiening (EFI, LBL)
LJUNG 73 PR D8 1307 +Cline (WISC)
Also 72 PRL 28 523 Ljung (WISC)
Also 72 PRL 28 1287 Cline, Ljung (WISC)
Also 69 PRL 23 326 Camerini, Ljung, Sheaff, Cline (WISC)
LUCAS 73 PR D8 719 +Taft, Willis (YALE)
LUCAS 73B PR D8 727 +Taft, Willis (YALE)
PANG 73 PR D8 1989 +Hildebrand, Cable, Stiening (EFI, ARIZ, LBL)
Also 72 PL 40B 699 Cable, Hildebrand, Pang, Stiening (EFI, LBL)
SMITH 73 NP B60 411 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ABRAMS 72 PRL 29 1118 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
ANKENBRA... 72 PRL 28 1472 Ankenbrandt, Larsen+ (BNL, LASL, FNAL, YALE)
AUBERT 72 NC 12A 509 +Heusse, Pascaud, Vialle+ (ORSAY, BRUX, EPOL)
BEIER 72 PRL 29 678 +Buchholz, Mann, Parker (PENN)
CHIANG 72 PR D6 1254 +Rosen, Shapiro, Handler, Olsen+ (ROCH, WISC)
CLARK 72 PRL 29 1274 +Cork, Elioff, Kerth, McReynolds, Newton+ (LBL)
EDWARDS 72 PR D5 2720 +Beier, Bertram, Herzo, Koester+ (ILL)
FORD 72 PL 38B 335 +Piroue, Remmel, Smith, Souder (PRIN)
HOFFMASTER 72 NP B36 1 +Koller, Taylor+ (STEV, SETO, LEHI)
BASILE 71C PL 36B 619 +Brehin, Diamant-Berger, Kunz+ (SACL, GEVA)
BOURQUIN 71 PL 36B 615 +Boymond, Extermann, Marasco+ (GEVA, SACL)
GINSBERG 71 PR D4 2893 (MIT)
HAIDT 71 PR D3 10 (AACH, BARI, CERN, EPOL, NIJM+)
Also 69 PL 29B 691 Haidt+ (AACH, BARI, CERN, EPOL, NIJM, ORSAY+)
KLEMS 71 PR D4 66 +Hildebrand, Stiening (CHIC, LRL)
Also 70 PRL 24 1086 Klems, Hildebrand, Stiening (LRL, CHIC)
Also 70B PRL 25 473 Klems, Hildebrand, Stiening (LRL, CHIC)
OTT 71 PR D3 52 +Pritchard (LOQM)
ROMANO 71 PL 36B 525 +Renton, Aubert, Burban-Lutz (BARI, CERN, ORSAY)
SCHWEINB... 71 PL 36B 246 Schweinberger (AACH, BELG, CERN, NIJM+)
STEINER 71 PL 36B 521 (AACH, BARI, CERN, EPOL, ORSAY, NIJM, PADO+)
BARDIN 70 PL 32B 121 +Bilenky, Pontecorvo (JINR)
BECHERRAWY 70 PR D1 1452 (ROCH)
BOTTERILL 70 PL 31B 325 +Brown, Clegg, Corbett, Culligan+ (OXF)
FORD 70 PRL 25 1370 +Piroue, Remmel, Smith, Souder (PRIN)
GAILLARD 70 CERN 70-14 +Chounet (CERN, ORSAY)
GINSBERG 70 PR D1 229 (HAIF)
GRAUMAN 70 PR D1 1277 +Koller, Taylor, Pandoulas+ (STEV, SETO, LEHI)
Also 69 PRL 23 737 Grauman, Koller, Taylor+ (STEV, SETO, LEHI)
MALTSEV 70 SJNP 10 678 +Pestova, Solodovnikova, Fadeev+ (JINR)
Translated from YAF 10 1195.
PANDOULAS 70 PR D2 1205 +Taylor, Koller, Grauman+ (STEV, SETO)
CUTTS 69 PR 184 1380 +Stiening, Wiegand, Deutsch (LRL, MIT)
Also 68 PRL 20 955 Cutts, Stiening, Wiegand, Deutsch (LRL, MIT)
DAVISON 69 PR 180 1333 +Bacastow, Barkas, Evans, Fung, Porter+ (UCR)
ELY 69 PR 180 1319 +Gidal, Hagopian, Kalmus+ (LOUC, WISC, LRL)
EMMERSON 69 PRL 23 393 +Quirk (OXF)
HERZO 69 PR 186 1403 +Banner, Beier, Bertram, Edwards+ (ILL)
KIJEWSKI 69 Thesis UCRL 18433 (LBL)
LOBKOWICZ 69 PR 185 1676 +Melissinos, Nagashima, Tewksbury+ (ROCH, BNL)
Also 66 PRL 17 548 Lobkowicz, Melissinos, Nagashima+ (ROCH, BNL)
MACEK 69 PRL 22 32 +Mann, McFarlane, Roberts+ (PENN, TEMP)
MAST 69 PR 183 1200 +Gershwin, Alston-Garnjost, Bangerter+ (LRL)
SELLERI 69 NC 60A 291
ZELLER 69 PR 182 1420 +Haddock, Helland, Pahl+ (UCLA, LRL)
BETTELS 68 NC 56A 1106 (AACH, BARI, BERG, CERN, EPOL, NIJM, ORSAY+)
Also 71 PR D3 10 Haidt (AACH, BARI, CERN, EPOL, NIJM+)
BOTTERILL 68B PRL 21 766 +Brown, Clegg, Corbett+ (OXF)
BOTTERILL 68C PR 174 1661 +Brown, Clegg, Corbett+ (OXF)
BUTLER 68 UCRL 18420 +Bland, Goldhaber, Goldhaber, Hirata+ (LRL)
CHANG 68 PRL 20 510 +Yodh, Ehrlich, Plano+ (UMD, RUTG)
CHEN 68 PRL 20 73 +Cutts, Kijewski, Stiening+ (LRL, MIT)
EICHTEN 68 PL 27B 586 (AACH, BARI, CERN, EPOL, ORSAY, PADO, VALE)
EISLER 68 PR 169 1090 +Fung, Marateck, Meyer, Plano (RUTG)
ESCHSTRUTH 68 PR 165 1487 +Franklin, Hughes+ (PRIN, PENN)
GARLAND 68 PR 167 1225 +Tsipis, Devons, Rosen+ (COLU, RUTG, WISC)
MOSCOSO 68 Thesis (ORSAY)
AUERBACH 67 PR 155 1505 +Dobbs, Mann+ (PENN, PRIN)
Also 74 PR D9 3216 Auerbach
Erratum.
BELLOTTI 67 Heidelberg Conf. +Pullia (MILA)
BELLOTTI 67B NC 52A 1287 +Fiorini, Pullia (MILA)
Also 66B PL 20 690 Bellotti, Fiorini, Pullia+ (MILA)
BISI 67 PL 25B 572 +Cester, Chiesa, Vigone (TORI)
BOTTERILL 67 PRL 19 982 +Brown, Corbett, Culligan+ (OXF)
Also 68 PR 171 1402 Botterill, Brown, Clegg, Corbett+ (OXF)
BOWEN 67B PR 154 1314 +Mann, McFarlane, Hughes+ (PPA)
CLINE 67B Herceg Novi Tbl. 4
Proc. International School on Elementary Particle Physics.
FLETCHER 67 PRL 19 98 +Beier, Edwards+ (ILL)
FORD 67 PRL 18 1214 +Lemonick, Nauenberg, Piroue (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
IMLAY 67 PR 160 1203 +Eschstruth, Franklin+ (PRIN)
KALMUS 67 PR 159 1187 +Kernan (LRL)
ZINCHENKO 67 Thesis Rutgers (RUTG)
CALLAHAN 66 NC 44A 90 (WISC)
CALLAHAN 66B PR 150 1153 +Camerini+ (WISC, LRL, UCR, BARI)
CESTER 66 PL 21 343 +Eschstruth, Oneill+ (PPA)
See footnote 1 in AUERBACH 67.
Also 67 PR 155 1505 Auerbach, Dobbs, Mann+ (PENN, PRIN)
BIRGE 65 PR 139B 1600 +Ely, Gidal, Camerini, Cline+ (LRL, WISC)
BISI 65 NC 35 768 +Borreani, Cester, Ferraro+ (TORI)
BISI 65B PR 139B 1068 +Borreani, Marzari-Chiesa, Rinaudo+ (TORI)
BORREANI 65 PR 140B 1686 +Gidal, Rinaudo, Caforio+ (BARI, TORI)
CALLAHAN 65 PRL 15 129 +Cline (WISC)
CAMERINI 65 NC 37 1795 +Cline, Gidal, Kalmus, Kernan (WISC, LRL)
CLINE 65 PL 15 293 +Fry (WISC)
CUTTS 65 PR 138B 969 +Elioff, Stiening (LRL)
DEMARCO 65 PR 140B 1430 +Grosso, Rinaudo (TORI, CERN)
FITCH 65B PR 140B 1088 +Quarles, Wilkins (PRIN, MTHO)
GREINER 65 ARNS 15 67 (LRL)
STAMER 65 PR 138B 440 +Huetter, Koller, Taylor, Grauman (STEV)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 5.
YOUNG 65 Thesis UCRL 16362 (LRL)
Also 67 PR 156 1464 Young, Osborne, Barkas (LRL)
BORREANI 64 PL 12 123 +Rinaudo, Werbrouck (TORI)
CALLAHAN 64 PR 136B 1463 +March, Stark (WISC)
CAMERINI 64 PRL 13 318 +Cline, Fry, Powell (WISC, LRL)
CLINE 64 PRL 13 101 +Fry (WISC)
GIACOMELLI 64 NC 34 1134 +Monti, Quareni+ (BGNA, MUNI)
GREINER 64 PRL 13 284 +Osborne, Barkas (LRL)
JENSEN 64 PR 136B 1431 +Shaklee, Roe, Sinclair (MICH)
KALMUS 64 PRL 13 99 +Kernan, Pu, Powell, Dowd (LRL, WISC)
SHAKLEE 64 PR 136B 1423 +Jensen, Roe, Sinclair (MICH)
BARKAS 63 PRL 11 26 +Dyer, Heckman (LRL)
BOYARSKI 62 PR 128 2398 +Loh, Niemela, Ritson (MIT)
BROWN 62B PRL 8 450 +Kadyk, Trilling, Roe+ (LRL, MICH)
BARKAS 61 PR 124 1209 +Dyer, Mason, Norris, Nickols, Smit (LRL)
BHOWMIK 61 NC 20 857 +Jain, Mathur (DELH)
FERRO-LUZZI 61 NC 22 1087 +Miller, Murray, Rosenfeld+ (LRL)
NORDIN 61 PR 123 2166 (LRL)
ROE 61 PRL 7 346 +Sinclair, Brown, Glaser+ (MICH, LRL)
FREDEN 60B PR 118 564 +Gilbert, White (LRL)
BURROWES 59 PRL 2 117 +Caldwell, Frisch, Hill+ (MIT)
TAYLOR 59 PR 114 359 +Harris, Orear, Lee, Baumel (COLU)
EISENBERG 58 NC 8 663 +Koch, Lohrmann, Nikolic+ (BERN)
ALEXANDER 57 NC 6 478 +Johnston, Oceallaigh (DUUC)
COHEN 57 Fund. Cons. Phys. +Crowe, Dumond (NAAS, LRL, CIT)
COOMBES 57 PR 108 1348 +Cork, Galbraith, Lambertson, Wenzel (LBL)
BIRGE 56 NC 4 834 +Perkins, Peterson, Stork, Whitehead (LRL)
ILOFF 56 PR 102 927 +Goldhaber, Lannutti, Gilbert+ (LRL)

OTHER RELATED PAPERS

LITTENBERG 93 ARNPS 43 729 +Valencia (BNL, FNAL)
Rare and Radiative Kaon Decays
RITCHIE 93 RMP 65 1149 +Wojcicki
"Rare *K* Decays"
BATTISTON 92 PRPL 214 293 +Cocolicchio, Fogli, Paver (PGIA, CERN, TRSTT)
Status and Perspectives of *K* Decay Physics
BRYMAN 89 IJMP A4 79 (TRIU)
"Rare Kaon Decays"
CHOUNET 72 PRPL 4C 199 +Gaillard, Gaillard (ORSAY, CERN)
FEARING 70 PR D2 542 +Fischbach, Smith (STON, BOHR)
HAIDT 69B PL 29B 696 + (AACH, BARI, CERN, EPOL, NIJM, ORSAY+)
CRONIN 68B Vienna Conf. 241 (PRIN)
Rapporteur talk.
WILLIS 67 Heidelberg Conf. 273 (YALE)
Rapporteur talk.
CABIBBO 66 Berkeley Conf. 33 (CERN)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
CABIBBO 64 PL 9 352 +Maksymowicz (CERN)
Also 64B PL 11 360 Cabibbo, Maksymowicz (CERN)
Also 65 PL 14 72 Cabibbo, Maksymowicz (CERN)
BIRGE 63 PRL 11 35 +Ely, Gidal, Camerini+ (LRL, WISC, BARI)
BLOCK 62B CERN Conf. 371 +Lendinara, Monari (NWES, BGNA)
BRENE 61 NP 22 553 +Egardt, Qvist (NORD)

K^0

$I(J^P) = \frac{1}{2}(0^-)$

K^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
497.672±0.031 OUR FIT					
497.672±0.031 OUR AVERAGE					
497.661±0.033	3713	BARKOV	87B	CMD	$e^+e^- \to K^0_L K^0_S$
497.742±0.085	780	BARKOV	85B	CMD	$e^+e^- \to K^0_L K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
497.44 ±0.50		FITCH	67	OSPK	
498.9 ±0.5	4500	BALTAY	66	HBC	K^0 from $\overline{p}p$
497.44 ±0.33	2223	KIM	65B	HBC	K^0 from $\overline{p}p$
498.1 ±0.4		CHRISTENS...	64	OSPK	

$m_{K^0} - m_{K^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.995±0.034 OUR FIT Error includes scale factor of 1.1.						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.95 ±0.21	417	HILL	68B	DBC	+	$K^+d \to K^0pp$
3.90 ±0.25	9	BURNSTEIN	65	HBC	−	
3.71 ±0.35	7	KIM	65B	HBC	−	$K^-p \to n\overline{K}^0$
5.4 ±1.1		CRAWFORD	59	HBC	+	
3.9 ±0.6		ROSENFELD	59	HBC	−	

$|m_{K^0} - m_{\overline{K}^0}| \,/\, m_{\text{average}}$

A test of *CPT* invariance.

VALUE	DOCUMENT ID
$<10^{-18}$ OUR EVALUATION	

K^0 REFERENCES

BARKOV	87B	SJNP 46 630 Translated from YAF 46 1088.	+Vasserman, Vorobev, Ivanov+	(NOVO)
BARKOV	85B	JETPL 42 138 Translated from ZETFP 42 113.	+Blinov, Vasserman+	(NOVO)
HILL	68B	PR 168 1534	+Robinson, Sakitt, Canter	(BNL, CMU)
FITCH	67	PR 164 1711	+Roth, Russ, Vernon	(PRIN)
BALTAY	66	PR 142 932	+Sandweiss, Stonehill+	(YALE, BNL)
BURNSTEIN	65	PR 138B 895	+Rubin	(UMD)
KIM	65B	PR 140B 1334	+Kirsch, Miller	(COLU)
CHRISTENS...	64	PRL 13 138	Christenson, Cronin, Fitch, Turlay	(PRIN)
CRAWFORD	59	PRL 2 112	+Cresti, Good, Stevenson, Ticho	(LRL)
ROSENFELD	59	PRL 2 110	+Solmitz, Tripp	(LRL)

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

K^0_S MEAN LIFE

For earlier measurements, beginning with BOLDT 58B, see our our 1986 edition, Physics Letters **170B** 130 (1986).

OUR FIT is described in the note on "Fits for K^0_L *CP*-Violation Parameters" in the K^0_L Particle Listings.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.8934±0.0008 OUR FIT					
0.8940±0.0009 OUR AVERAGE					
0.8971±0.0021		BERTANZA	97	NA31	
0.8941±0.0014±0.0009		SCHWINGEN...	95	E773	Δm free, $\phi_{+-}=\phi_{SW}$
0.8929±0.0016		GIBBONS	93	E731	
0.8920±0.0044	214k	GROSSMAN	87	SPEC	
0.881 ±0.009	26k	ARONSON	76	SPEC	
0.8924±0.0032		[1] CARITHERS	75	SPEC	
0.8937±0.0048	6M	GEWENIGER	74B	ASPK	
0.8958±0.0045	50k	[2] SKJEGGEST...	72	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.905 ±0.007		[3] ARONSON	82B	SPEC	
0.867 ±0.024	2173	[4] FACKLER	73	OSPK	
0.856 ±0.008	19994	[5] DONALD	68B	HBC	
0.872 ±0.009	20000	[5,6] HILL	68	DBC	
0.866 ±0.016		[5] ALFF-...	66B	OSPK	
0.843 ±0.013	5000	[5] KIRSCH	66	HBC	

[1] CARITHERS 75 value is for $m_{K^0_L} - m_{K^0_S}$ $\Delta m = 0.5301 \pm 0.0013$. The Δm dependence of the total decay rate (inverse mean life) is $\Gamma(K^0_S) = [(1.122 \pm 0.004) + 0.16(\Delta m - 0.5348)/\Delta m]10^{10}/\text{s}$, or, in terms of meanlife $\tau_s = 0.8913 \pm 0.0032 - 0.238(\Delta m - 0.5348)$ where Δm and τ_s are in units of $10^{10}\hbar\text{s}^{-1}$ and 10^{-10}s respectively.

[2] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

[3] ARONSON 82 find that K^0_S mean life may depend on the kaon energy.

[4] FACKLER 73 does not include systematic errors.

[5] Pre-1971 experiments are excluded from the average because of disagreement with later more precise experiments.

[6] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

K^0_S DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-$		(68.61 ± 0.28) %	S=1.2
Γ_2	$\pi^0\pi^0$		(31.39 ± 0.28) %	S=1.2
Γ_3	$\pi^+\pi^-\gamma$	[a,b]	$(1.78\pm0.05) \times 10^{-3}$	
Γ_4	$\gamma\gamma$		$(2.4\pm0.9) \times 10^{-6}$	
Γ_5	$\pi^+\pi^-\pi^0$		$(3.4^{+1.1}_{-0.9}) \times 10^{-7}$	
Γ_6	$3\pi^0$		$< 3.7 \times 10^{-5}$	CL=90%
Γ_7	$\pi^\pm e^\mp \nu$	[c]	$(6.70\pm0.07) \times 10^{-4}$	S=1.1
Γ_8	$\pi^\pm \mu^\mp \nu$	[c]	$(4.69\pm0.06) \times 10^{-4}$	S=1.1
$\Delta S = 1$ weak neutral current (*S1*) modes				
Γ_9	$\mu^+\mu^-$	*S1*	$< 3.2 \times 10^{-7}$	CL=90%
Γ_{10}	e^+e^-	*S1*	$< 1.4 \times 10^{-7}$	CL=90%
Γ_{11}	$\pi^0 e^+ e^-$	*S1*	$< 1.1 \times 10^{-6}$	CL=90%

[a] See the Particle Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] Calculated from K^0_L semileptonic rates and the K^0_S lifetime assuming $\Delta S = \Delta Q$.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 17 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 = 16.5$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|c} x_2 & -100 \\ \hline & x_1 \end{array}$$

K^0_S DECAY RATES

$\Gamma(\pi^\pm e^\mp \nu)$ — Γ_7

VALUE (10^6 s^{-1})	DOCUMENT ID		TECN	COMMENT
7.50±0.08 OUR EVALUATION	Error includes scale factor of 1.1. From K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm e^\mp \nu) = \Gamma(K^0_L \to \pi^\pm e^\mp \nu_e)$.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BURGUN	72	HBC	$K^+p \to K^0 p\pi^+$
9.3 ±2.5	AUBERT	65	HLBC	$\Delta S=\Delta Q$, *CP* cons. not assumed

$\Gamma(\pi^\pm \mu^\mp \nu)$ — Γ_8

VALUE (10^6 s^{-1})	DOCUMENT ID
5.25±0.07 OUR EVALUATION	Error includes scale factor of 1.1. From K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm \mu^\mp \nu) = \Gamma(K^0_L \to \pi^\pm \mu^\mp \nu)$.

K^0_S BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.6861±0.0028 OUR FIT Error includes scale factor of 1.2.					
0.671 ±0.010 OUR AVERAGE					
0.670 ±0.010	3447	[7] DOYLE	69	HBC	$\pi^-p \to \Lambda K^0$
0.70 ±0.08		COLUMBIA	60B	HBC	
0.68 ±0.04		CRAWFORD	59B	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.740 ±0.024		[7] ANDERSON	62B	HBC	

[7] Anderson result not published, events added to Doyle sample.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.186±0.028 OUR FIT	Error includes scale factor of 1.2.			
2.197±0.026 OUR AVERAGE				
2.11 ±0.09	1315	EVERHART 76	WIRE	$\pi^- p \to \Lambda K^0$
2.169±0.094	16k	COWELL 74	OSPK	$\pi^- p \to \Lambda K^0$
2.16 ±0.08	4799	HILL 73	DBC	$K^+ d \to K^0 pp$
2.22 ±0.10	3068	[8] ALITTI 72	HBC	$K^+ p \to \pi^+ p K^0$
2.22 ±0.08	6380	MORSE 72B	DBC	$K^+ n \to K^0 p$
2.10 ±0.11	701	[9] NAGY 72	HLBC	$K^+ n \to K^0 p$
2.22 ±0.095	6150	[10] BALTAY 71	HBC	$K p \to K^0$ neutrals
2.282±0.043	7944	[11] MOFFETT 70	OSPK	$K^+ n \to K^0 p$
2.10 ±0.06	3700	MORFIN 69	HLBC	$K^+ n \to K^0 p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.12 ±0.17	267	[9] BOZOKI 69	HLBC	
2.285±0.055	3016	[11] GOBBI 69	OSPK	$K^+ n \to K^0 p$

[8] The directly measured quantity is $K^0_S \to \pi^+\pi^-/\text{all } K^0 = 0.345 \pm 0.005$.

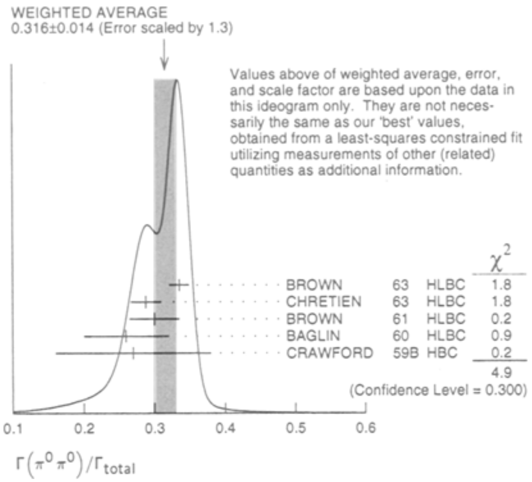
[9] NAGY 72 is a final result which includes BOZOKI 69.

[10] The directly measured quantity is $K^0_S \to \pi^+\pi^-/\text{all } \overline{K}^0 = 0.345 \pm 0.005$.

[11] MOFFETT 70 is a final result which includes GOBBI 69.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN
0.3139±0.0028 OUR FIT	Error includes scale factor of 1.2.		
0.316 ±0.014 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.		
0.335 ±0.014	1066	BROWN 63	HLBC
0.288 ±0.021	198	CHRETIEN 63	HLBC
0.30 ±0.035		BROWN 61	HLBC
0.26 ±0.06		BAGLIN 60	HLBC
0.27 ±0.11		CRAWFORD 59B	HBC



$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.60±0.08 OUR AVERAGE				
2.56±0.09	1286	RAMBERG 93	E731	p_γ >50 MeV/c
2.68±0.15		[12] TAUREG 76	SPEC	p_γ >50 MeV/c
2.8 ±0.6		[13] BURGUN 73	HBC	p_γ >50 MeV/c
3.3 ±1.2	10	WEBBER 70	HBC	p_γ >50 MeV/c
no ratio given	27	BELLOTTI 66	HBC	p_γ >50 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.10±0.22	3723	RAMBERG 93	E731	p_γ >20 MeV/c
3.0 ±0.6	29	[14] BOBISUT 74	HLBC	p_γ >40 MeV/c

[12] TAUREG 76 find direct emission contribution <0.06, CL = 90%.

[13] BURGUN 73 estimates that direct emission contribution is 0.3 ± 0.6.

[14] BOBISUT 74 not included in average because p_γ cut differs. Estimates direct emission contribution to be 0.5 or less, CL = 95%.

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
2.4±0.9		35	[15] BARR 95B	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.2±1.1		16	[16] BARR 95B	NA31	
< 13	90		BALATS 89	SPEC	
2.4±1.2		19	BURKHARDT 87	NA31	
< 133	90		BARMIN 86B	XEBC	
< 200	90		VASSERMAN 86	CALO	$\phi \to K^0_S K^0_L$
< 400	90	0	BARMIN 73B	HLBC	
< 710	90	0	[17] BANNER 72B	OSPK	
< 2000	90	0	MORSE 72B	DBC	
< 2200	90	0	[17] REPELLIN 71	OSPK	
<21000	90	0	[17] BANNER 69	OSPK	

[15] BARR 95B quotes this as the combined BARR 95B + BURKHARDT 87 result after rescaling BURKHARDT 87 to use same branching ratios and lifetimes as BARR 95B.

[16] BARR 95B result is calculated using $B(K_L \to \gamma\gamma) = (5.86 \pm 0.17) \times 10^{-4}$.

[17] These limits are for maximum interference in K^0_S-K^0_L to 2γ's.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$3.4^{+1.1}_{-0.9}$ OUR AVERAGE					
$2.5^{+1.3+0.5}_{-1.0-0.6}$		500k	[18] ADLER 97B	CPLR	
$4.1^{+2.5+0.5}_{-1.9-0.6}$			[19] ADLER 96E	CPLR	
$4.8^{+2.2}_{-1.6}\pm1.1$			[20] ZOU 96	E621	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.9^{+5.4+0.9}_{-1.8-0.7}$			[21] THOMSON 94	E621	Sup. by ZOU 96
<490	90		[22] BARMIN 85	HLBC	
<850	90		METCALF 72	ASPK	

[18] ADLER 97B find the *CP*-conserving parameters $\text{Re}(\lambda) = (28 \pm 7 \pm 3) \times 10^{-3}$, $\text{Im}(\lambda) = (-10 \pm 8 \pm 2) \times 10^{-3}$. They estimate $B(K^0_S \to \pi^+\pi^-\pi^0)$ from $\text{Re}(\lambda)$ and the K^0_L decay parameters.

[19] ADLER 96E is from the measured quantities $\text{Re}(\lambda) = 0.036 \pm 0.010^{+0.002}_{-0.003}$ and $\text{Im}(\lambda)$ consistent with zero. Note that the quantity λ is the same as ρ_{+-0} used in other footnotes.

[20] ZOU 96 is from the the measured quantities $|\rho_{+-0}| = 0.039^{+0.009}_{-0.006} \pm 0.005$ and $\phi_\rho = (-9 \pm 18)^\circ$.

[21] THOMSON 94 calculates this branching ratio from their measurements $|\rho_{+-0}| = 0.035^{+0.019}_{-0.011} \pm 0.004$ and $\phi_\rho = (-59 \pm 48)^\circ$ where $|\rho_{+-0}| e^{i\phi_\rho} = A(K^0_S \to \pi^+\pi^-\pi^0, I=2)/A(K^0_L \to \pi^+\pi^-\pi^0)$.

[22] BARMIN 85 assumes that *CP*-allowed and *CP*-violating amplitudes are equally suppressed.

$\Gamma(3\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<0.37	90	BARMIN 83	HLBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<4.3	90	BARMIN 73	HLBC

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_9/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN
< 0.032	90	GJESDAL 73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<14	90	BOHM 69	OSPK
< 0.7	90	HYAMS 69B	OSPK
<22	90	[23] STUTZKE 69	OSPK
< 7	90	BOTT-... 67	OSPK

[23] Value calculated by us, using 2.3 instead of 1 event, 90% CL.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.4	90		ANGELOPO... 97	CPLR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 28	90	0	BLICK 94	CNTR	Hyperon facility
< 100	90		BARMIN 86	XEBC	
<1100	90		BITSADZE 86	CALO	
<3400	90		BOHM 69	OSPK	

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN
< 1.1	90	0	BARR 93B	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<45	90		GIBBONS 88	E731

CP VIOLATION IN $K_S \to 3\pi$

Written 1996 by T. Nakada (Paul Scherrer Institute) and L. Wolfenstein (Carnegie-Mellon University).

The possible final states for the decay $K^0 \to \pi^+\pi^-\pi^0$ have isospin $I = 0$, 1, 2, and 3. The $I = 0$ and $I = 2$ states have $CP = +1$ and K_S can decay into them without violating CP symmetry, but they are expected to be strongly suppressed by centrifugal barrier effects. The $I = 1$ and $I = 3$ states, which have no centrifugal barrier, have $CP = -1$ so that the K_S decay to these requires CP violation.

In order to see CP violation in $K_S \to \pi^+\pi^-\pi^0$, it is necessary to observe the interference between K_S and K_L decay, which determines the amplitude ratio

$$\eta_{+-0} = \frac{A(K_S \to \pi^+\pi^-\pi^0)}{A(K_L \to \pi^+\pi^-\pi^0)} \ .$$

If η_{+-0} is obtained from an integration over the whole Dalitz plot, there is no contribution from the $I = 0$ and $I = 2$ final states and a nonzero value of η_{+-0} is entirely due to CP violation.

Only $I = 1$ and $I = 3$ states, which are $CP = -1$, are allowed for $K^0 \to \pi^0\pi^0\pi^0$ decays and the decay of K_S into $3\pi^0$ is an unambiguous sign of CP violation. Similarly to η_{+-0}, η_{000} is defined as

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \ .$$

If one assumes that CPT invariance holds and that there are no transitions to $I = 3$ (or to nonsymmetric $I = 1$ states), it can be shown that

$$\begin{aligned} \eta_{+-0} &= \eta_{000} \\ &= \epsilon + i\frac{\operatorname{Im} a_1}{\operatorname{Re} a_1} \ . \end{aligned}$$

With the Wu-Yang phase convention, a_1 is the weak decay amplitude for K^0 into $I = 1$ final states; ϵ is determined from CP violation in $K_L \to 2\pi$ decays. The real parts of η_{+-0} and η_{000} are equal to $\operatorname{Re}(\epsilon)$. Since currently-known upper limits on $|\eta_{+-0}|$ and $|\eta_{000}|$ are much larger than $|\epsilon|$, they can be interpreted as upper limits on $\operatorname{Im}(\eta_{+-0})$ and $\operatorname{Im}(\eta_{000})$ and so as limits on the CP-violating phase of the decay amplitude a_1.

CP-VIOLATION PARAMETERS IN K^0_S DECAY

$\operatorname{Im}(\eta_{+-0})^2 = \Gamma(K^0_S \to \pi^+\pi^-\pi^0, CP\text{-violating}) / \Gamma(K^0_L \to \pi^+\pi^-\pi^0)$

CPT assumed valid (i.e. $\operatorname{Re}(\eta_{+-0}) \simeq 0$).

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.23	90	601	[24] BARMIN	85	HLBC	
<1.2	90	192	BALDO-...	75	HLBC	
<0.71	90	148	MALLARY	73	OSPK	Re(A)=−0.05 ± 0.17
<0.66	90	180	JAMES	72	HBC	
<1.2	90	99	JONES	72	OSPK	
<0.12	90	384	METCALF	72	ASPK	
<1.2	90	99	CHO	71	DBC	
<1.0	90	98	JAMES	71	HBC	Incl. in JAMES 72
<1.2	95	50	[25] MEISNER	71	HBC	CL=90% not avail.
<0.8	90	71	WEBBER	70	HBC	
<0.45	90		BEHR	66	HLBC	
<3.8	90	18	ANDERSON	65	HBC	Incl. in WEBBER 70

[24] BARMIN 85 find $\operatorname{Re}(\eta_{+-0}) = (0.05 \pm 0.17)$ and $\operatorname{Im}(\eta_{+-0}) = (0.15 \pm 0.33)$. Includes events of BALDO-CEOLIN 75.

[25] These authors find $\operatorname{Re}(A) = 2.75 \pm 0.65$, above value at $\operatorname{Re}(A) = 0$.

$\operatorname{Im}(\eta_{+-0}) = \operatorname{Im}(A(K^0_S \to \pi^+\pi^-\pi^0, CP\text{-violating}) / A(K^0_L \to \pi^+\pi^-\pi^0))$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
−0.002±0.008 OUR AVERAGE				
$-0.002\pm0.009^{+0.002}_{-0.001}$	500k	[26] ADLER	97B	CPLR
−0.002±0.018±0.003	137k	[27] ADLER	96D	CPLR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.015±0.017±0.025	272k	[28] ZOU	94	SPEC

[26] ADLER 97B also find $\operatorname{Re}(\eta_{+-0}) = -0.002 \pm 0.007^{+0.004}_{-0.001}$.

[27] The ADLER 96D fit also yields $\operatorname{Re}(\eta_{+-0}) = 0.006 \pm 0.013 \pm 0.001$ with a correlation $+0.66$ between real and imaginary parts. Their results correspond to $|\eta_{+-0}| < 0.037$ with 90% CL.

[28] ZOU 94 use theoretical constraint $\operatorname{Re}(\eta_{+-0}) = \operatorname{Re}(\epsilon) = 0.0016$. Without this constraint they find $\operatorname{Im}(\eta_{+-0}) = 0.019 \pm 0.061$ and $\operatorname{Re}(\eta_{+-0}) = 0.019 \pm 0.027$.

$\operatorname{Im}(\eta_{000})^2 = \Gamma(K^0_S \to 3\pi^0) / \Gamma(K^0_L \to 3\pi^0)$

CPT assumed valid (i.e. $\operatorname{Re}(\eta_{000}) \simeq 0$). This limit determines branching ratio $\Gamma(3\pi^0)/\Gamma_{\text{total}}$ above.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.1	90	632	[29] BARMIN	83	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.28	90		[30] GJESDAL	74B	SPEC	Indirect meas.
<1.2	90	22	BARMIN	73	HLBC	

[29] BARMIN 83 find $\operatorname{Re}(\eta_{000}) = (-0.08 \pm 0.18)$ and $\operatorname{Im}(\eta_{000}) = (-0.05 \pm 0.27)$. Assuming *CPT* invariance they obtain the limit quoted above.

[30] GJESDAL 74B uses $K2\pi$, $K_{\mu3}$, and K_{e3} decay results, unitarity, and *CPT*. Calculates $|(\eta_{000})| = 0.26 \pm 0.20$. We convert to upper limit.

K^0_S REFERENCES

ADLER	97B	PL B407 193	R. Adler+	(CPLEAR Collab.)
ANGELOPO...	97	PL B413 232	A. Angelopoulos+	(CPLEAR Collab.)
BERTANZA	97	ZPHY C73 629	L. Bertanza	(PISA, CERN, EDIN, MANZ, ORSAY, SIEG)
ADLER	96D	PL B370 167	+Alhalel, Angelopoulos+	(CPLEAR Collab.)
ADLER	96E	PL B374 313	+Alhalel, Angelopoulos+	(CPLEAR Collab.)
ZOU	96	PL B369 362	+Beretvas, Caracappa+	(RUTG, MINN, MICH)
BARR	95B	PL B351 579	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
SCHWINGEN...	95	PRL 74 4376	Schwingenheuer+	(EFI, CHIC, ELMT, FNAL, ILL, RUTG)
BLICK	94	PL B334 234	+Kolosov, Kutjin, Shelikov+	(SERP, JINR)
THOMSON	94	PL B337 411	+Zou, Beretvas, Caracappa, Devlin+	(RUTG, MINN, MICH)
ZOU	94	PL B329 519	+Beretvas, Caracappa, Devlin+	(RUTG, MINN, MICH)
BARR	93B	PL B304 381	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
GIBBONS	93	PRL 70 1199	+Barker, Briere, Makoff+	(FNAL E731 Collab.)
Also	97	PR D55 6625	L.K. Gibbons+	(FNAL E731 Collab.)
RAMBERG	93	PRL 70 2525	+Bock, Coleman, Enagonio, Hsiung+	(FNAL E731 Collab.)
BALATS	89	SJNP 49 828 Translated from YAF 49 1332.	+Berezin, Bogdanov, Vishnevskii, Vishnyakov+	(ITEP)
GIBBONS	88	PRL 61 2661	+Papadimitriou+	(FNAL E731 Collab.)
BURKHARDT	87	PL B199 139	+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
GROSSMAN	87	PRL 59 18	+Heller, James, Shupe+	(MINN, MICH, RUTG)
BARMIN	86	SJNP 44 622 Translated from YAF 44 965.	+Barylov, Davidenko, Demidov+	(ITEP)
BARMIN	86B	NC 96A 159	+Barylov, Chistyakova, Chuvilo+	(ITEP, PADO)
BITSADZE	86	PL 167B 138	+Budagov	(CMNS, SOFI, SERP, TBIL, JINR, BAKU+)
PDG	86B	PL 170B 130	Aguilar-Benitez, Porter+	(CERN, CIT+)
VASSERMAN	86	JETPL 43 588 Translated from ZETFP 43 457.	+Golubev, Gluskin, Druzhinin+	(NOVO)
BARMIN	85	NC 85A 67	+Barylov, Chistyakova, Chuvilo+	(ITEP, PADO)
Also	85B	SJNP 41 759 Translated from YAF 41 1187.	Barmin, Barylov, Volkov+	(ITEP)
BARMIN	83	PL 128B 129	+Barylov, Chistyakova, Chuvilo+	(ITEP, PADO)
Also	84	SJNP 39 269 Translated from YAF 39 428.	Barmin, Barylov, Golubchikov+	(ITEP, PADO)
ARONSON	82	PRL 48 1078	+Bernstein+	(BNL, CHIC, STAN, WISC)
ARONSON	82B	PRL 48 1306	+Bock, Cheng, Fischbach	(BNL, CHIC, PURD)
Also	82B	PL 116B 73	Fischbach, Cheng+	(PURD, BNL, CHIC)
Also	83	PR D28 476	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
Also	83B	PR D28 495	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
ARONSON	76	NC 32A 236	+McIntyre, Roehrig+	(WISC, EFI, UCSD, ILLC)
EVERHART	76	PR D14 661	+Kraus, Lande, Long, Lowenstein+	(PENN)
TAUREG	76	PL 65B 92	+Zech, Dydak, Navarria+	(HEIDH, CERN, DORT)
BALDO-...	75	NC 25A 688	Baldo-Ceolin, Bobisut, Calimani+	(PADO, WISC)
CARITHERS	75	PRL 34 1244	+Modis, Nygren, Pun+	(COLU, NYU)
BOBISUT	74	LNC 11 646	+Huzita, Mattioli, Puglierin	(PADO)
COWELL	74	PR D10 2083	+Lee-Franzini, Orcutt, Franzini+	(STON, COLU)
GEWENIGER	74B	PL 48B 487	+Gjesdal, Presser+	(CERN, HEIDH)
GJESDAL	74B	PL 52B 119	+Presser, Steffen+	(CERN, HEIDH)
BARMIN	73	PL 46B 465	+Barylov, Davidenko, Demidov+	(ITEP)
BARMIN	73B	PL 47B 463	+Barylov, Davidenko, Demidov+	(ITEP)
BURGUN	73	PL 46B 481	+Bertranet, Lesquoy, Muller, Pauli+	(SACL, CERN)
FACKLER	73	PRL 31 847	+Frisch, Martin, Smoot, Sompayrac	(MIT)
GJESDAL	73	PL 44B 217	+Presser, Steffen, Steinberger+	(CERN, HEIDH)
HILL	73	PR D8 1290	+Sakitt, Samios, Burris, Engler+	(BNL, CMU)
MALLARY	73	PR D7 1953	+Binnie, Gallivan, Gomez, Peck, Sciulli+	(CIT)
ALITTI	72	PL 39B 568	+Lesquoy, Muller	(SACL)
BANNER	72B	PRL 29 237	+Cronin, Hoffman, Knapp, Shochet	(PRIN)
BURGUN	72	NP B50 194	+Lesquoy, Muller, Pauli+	(SACL, CERN, OSLO)
JAMES	72	NP B49 1	+Montanet, Paul, Saetre+	(CERN, SACL, OSLO)
JONES	72	NC 9A 151	+Abashian, Graham, Mantsch, Orr, Smith+	(ILL)
METCALF	72	PL 40B 703	+Neuhofer, Niebergall+	(CERN, IPN, WIEN)
MORSE	72B	PRL 28 388	+Nauenberg, Bierman, Sager+	(COLO, PRIN, UMD)
NAGY	72	NP B47 94	+Telbisz, Vestergombi	(BUDA)
Also	69	PL 30B 498	Bozoki, Fenyves, Gombosi, Nagy+	(BUDA)
SKJEGGEST...	72	NP B48 343	Skjeggestad, James+	(OSLO, CERN, SACL)
BALTAY	71	PRL 27 1678	+Bridgewater, Cooper, Gershwin, Habibi+	(COLU)
Also	71	Thesis Nevis 187	Cooper	(COLU)
CHO	71	PR D3 1557	+Dralle, Canter, Engler, Fisk+	(CMU, BNL, CASE)
JAMES	71	PL 35B 265	+Montanet, Paul, Pauli+	(CERN, SACL, OSLO)
MEISNER	71	PR D3 59	+Mann, Hertzbach, Kofler+	(MASA, BNL, YALE)
REPELLIN	71	PL 36B 603	+Wolff, Chollet, Gaillard, Jane+	(ORSAY, CERN)
MOFFETT	70	BAPS 15 512	+Gobbi, Green, Hakel, Rosen	(ROCH)
WEBBER	70	PR D1 1967	+Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	69	Thesis UCRL 19226	Webber	(LRL)

BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
BOHM 69 Thesis (AACH)
BOZOKI 69 PL 30B 498 +Fenyves, Gombosi, Nagy+ (BUDA)
DOYLE 69 Thesis UCRL 18139 (LRL)
GOBBI 69 PRL 22 682 +Green, Hakel, Moffett, Rosen+ (ROCH)
HYAMS 69B PL 29B 521 +Koch, Potter, VonLindern, Lorenz+ (CERN, MPIM)
MORFIN 69 PRL 23 660 +Sinclair (MICH)
STUTZKE 69 PR 177 2009 +Abashian, Jones, Mantsch, Orr, Smith (ILL)
DONALD 68B PL 27B 58 +Edwards, Nisar+ (LIVP, CERN, IPNP, CDEF)
HILL 68 PR 171 1418 +Robinson, Sakitt+ (BNL, CMU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSAY)
BELLOTTI 66 NC 45A 737 +Pullia, Baldo-Ceolin+ (MILA, PADO)
KIRSCH 66 PR 147 939 +Schmidt (COLU)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
AUBERT 65 PL 17 59 +Behr, Canavan, Chounet+ (EPOL, ORSAY)
BROWN 63 PR 130 769 +Kadyk, Trilling, Roe+ (LRL, MICH)
CHRETIEN 63 PR 131 2208 + (BRAN, BROW, HARV, MIT)
ANDERSON 62B CERN Conf. 836 +Crawford+ (LRL)
BROWN 61 NC 19 1155 +Bryant, Burnstein, Glaser, Kadyk+ (MICH)
BAGLIN 60 NC 18 1043 +Bloch, Brisson, Hennessy+ (EPOL)
COLUMBIA 60B Rochester Conf. 727 Schwartz+ (COLU)
CRAWFORD 59B PRL 2 266 +Cresti, Douglass, Good, Ticho+ (LRL)
BOLDT 58B PRL 1 150 +Caldwell, Pal (MIT)

OTHER RELATED PAPERS

LITTENBERG 93 ARNPS 43 729 +Valencia (BNL, FNAL)
Rare and Radiative Kaon Decays
BATTISTON 92 PRPL 214 293 +Cocolicchio, Fogli, Paver (PGIA, CERN, TRSTT)
Status and Perspectives of *K* Decay Physics
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
CRAWFORD 62 CERN Conf. 827 (LRL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
BIRGE 60 Rochester Conf. 601 +Ely+ (LRL, WISC)
MULLER 60 PRL 4 418 +Birge, Fowler, Good, Piccioni+ (LRL, BNL)

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K^0_L} - m_{K^0_S}$

For earlier measurements, beginning with GOOD 61 and FITCH 61, see our 1986 edition, Physics Letters **170B** 132 (1986).

OUR FIT is described in the note on "Fits for K^0_L *CP*-Violation Parameters" in the K^0_L Particle Listings.

VALUE (10^{10} $\hbar$ s^{-1})	*DOCUMENT ID*		*TECN*	*COMMENT*
0.5301±0.0014	**OUR FIT**			
0.5311±0.0019	**OUR AVERAGE** Error includes scale factor of 1.2.			
0.5274±0.0029 ±0.0005	[1] ADLER	95	CPLR	
0.5297±0.0030 ±0.0022	[2] SCHWINGEN...	95	E773	20–160 GeV *K* beams
0.5257±0.0049 ±0.0021	[2] GIBBONS	93C	E731	20–160 GeV *K* beams
0.5340±0.00255±0.0015	[3] GEWENIGER	74C	SPEC	Gap method
0.5334±0.0040 ±0.0015	[3] GJESDAL	74	SPEC	Charge asymmetry in $K^0_{\ell 3}$
0.542 ±0.006	CULLEN	70	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5307±0.0013	[4] ADLER	96C	RVUE	
0.5286±0.0028	[5] GIBBONS	93	E731	20–160 GeV *K* beams
0.482 ±0.014	[6] ARONSON	82B	SPEC	E=30–110 GeV
0.534 ±0.007	[7] CARNEGIE	71	ASPK	Gap method
0.542 ±0.006	[7] ARONSON	70	ASPK	Gap method

[1] ADLER 95 uses $\overline{K}^0_{e3}$ and K^0_{e3} strangeness tagging at production and decay.

[2] Fits Δm and ϕ_{+-} simultaneously. GIBBONS 93C systematic error is from B. Winstein via private communtication.

[3] These two experiments have a common systematic error due to the uncertainty in the momentum scale, as pointed out in WAHL 89.

[4] ADLER 96C is the result of a fit which includes nearly the same data as entered into the "OUR FIT" value above.

[5] GIBBONS 93 value assume $\phi_{+-} = \phi_{00} = \phi_{SW} = (43.7 \pm 0.2)^\circ$.

[6] ARONSON 82 find that Δm may depend on the kaon energy.

[7] ARONSON 70 and CARNEGIE 71 use K^0_S mean life $= (0.862 \pm 0.006) \times 10^{-10}$ s. We have not attempted to adjust these values for the subsequent change in the K^0_S mean life or in η_{+-}.

K^0_L MEAN LIFE

VALUE (10^{-8} s)	*EVTS*	*DOCUMENT ID*		*TECN*
5.17 ±0.04	**OUR FIT** Error includes scale factor of 1.1.			
5.15 ±0.04	**OUR AVERAGE**			
5.154±0.044	0.4M	VOSBURGH	72	CNTR
5.15 ±0.14		DEVLIN	67	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.0 ±0.5		[8] LOWYS	67	HLBC
6.1 $^{+1.5}_{-1.2}$	1700	ASTBURY	65C	CNTR
5.3 ±0.6		FUJII	64	OSPK
5.1 $^{+2.4}_{-1.3}$	15	DARMON	62	FBC
8.1 $^{+3.2}_{-2.4}$	34	BARDON	58	CNTR

[8] Sum of partial decay rates.

K^0_L DECAY MODES

	Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$3\pi^0$			(21.12 ± 0.27) %	S=1.1
Γ_2	$\pi^+\pi^-\pi^0$			(12.56 ± 0.20) %	S=1.7
Γ_3	$\pi^\pm\mu^\mp\nu$		[a]	(27.17 ± 0.25) %	S=1.1
	Called $K^0_{\mu3}$.				
Γ_4	$\pi^-\mu^+\nu_\mu$				
Γ_5	$\pi^+\mu^-\overline{\nu}_\mu$				
Γ_6	$\pi^\pm e^\mp\nu_e$		[a]	(38.78 ± 0.27) %	S=1.1
	Called K^0_{e3}.				
Γ_7	$\pi^- e^+\nu_e$				
Γ_8	$\pi^+ e^-\overline{\nu}_e$				
Γ_9	2γ			$(5.92 \pm 0.15) \times 10^{-4}$	
Γ_{10}	3γ			$< 2.4 \times 10^{-7}$	CL=90%
Γ_{11}	$\pi^0 2\gamma$		[b]	$(1.70 \pm 0.28) \times 10^{-6}$	
Γ_{12}	$\pi^0\pi^\pm e^\mp\nu$		[a]	$(5.18 \pm 0.29) \times 10^{-5}$	
Γ_{13}	$(\pi\mu\,\text{atom})\nu$			$(1.06 \pm 0.11) \times 10^{-7}$	
Γ_{14}	$\pi^\pm e^\mp\nu_e\gamma$		[a,b,c]	$(3.62\ ^{+0.26}_{-0.21}) \times 10^{-3}$	
Γ_{15}	$\pi^+\pi^-\gamma$		[b,c]	$(4.61 \pm 0.14) \times 10^{-5}$	
Γ_{16}	$\pi^0\pi^0\gamma$			$< 5.6 \times 10^{-6}$	
	Charge conjugation × Parity (*CP, CPV*) or Lepton Family number (*LF*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes				
Γ_{17}	$\pi^+\pi^-$	*CPV*		$(2.067 \pm 0.035) \times 10^{-3}$	S=1.1
Γ_{18}	$\pi^0\pi^0$	*CPV*		$(9.36 \pm 0.20) \times 10^{-4}$	
Γ_{19}	$\mu^+\mu^-$	*S1*		$(7.2 \pm 0.5) \times 10^{-9}$	S=1.4
Γ_{20}	$\mu^+\mu^-\gamma$	*S1*		$(3.25 \pm 0.28) \times 10^{-7}$	
Γ_{21}	e^+e^-	*S1*		$< 4.1 \times 10^{-11}$	CL=90%
Γ_{22}	$e^+e^-\gamma$	*S1*		$(9.1 \pm 0.5) \times 10^{-6}$	
Γ_{23}	$e^+e^-\gamma\gamma$	*S1*	[b]	$(6.5 \pm 1.2) \times 10^{-7}$	
Γ_{24}	$\pi^+\pi^-e^+e^-$	*S1*	[b]	$< 4.6 \times 10^{-7}$	CL=90%
Γ_{25}	$\mu^+\mu^-e^+e^-$	*S1*		$(2.9\ ^{+6.7}_{-2.4}) \times 10^{-9}$	
Γ_{26}	$e^+e^-e^+e^-$	*S1*		$(4.1 \pm 0.8) \times 10^{-8}$	S=1.2
Γ_{27}	$\pi^0\mu^+\mu^-$	*CP,S1*	[d]	$< 5.1 \times 10^{-9}$	CL=90%
Γ_{28}	$\pi^0 e^+e^-$	*CP,S1*	[d]	$< 4.3 \times 10^{-9}$	CL=90%
Γ_{29}	$\pi^0\nu\overline{\nu}$	*CP,S1*	[e]	$< 5.8 \times 10^{-5}$	CL=90%
Γ_{30}	$e^\pm\mu^\mp$	*LF*	[a]	$< 3.3 \times 10^{-11}$	CL=90%
Γ_{31}	$e^\pm e^\pm\mu^\mp\mu^\mp$	*LF*	[a]	$< 6.1 \times 10^{-9}$	CL=90%

[a] The value is for the sum of the charge states of particle/antiparticle states indicated.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[d] Allowed by higher-order electroweak interactions.

[e] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 4 decay rate, and 12 branching ratios uses 46 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 41.2$ for 39 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i\delta p_j\right\rangle/(\delta p_i{\cdot}\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−19						
x_3	−37	−28					
x_6	−49	−28	−36				
x_9	−8	22	−6	−5			
x_{17}	−12	35	−8	−8	64		
x_{18}	−10	27	−7	−6	84	77	
Γ	0	0	0	0	0	0	0
	x_1	x_2	x_3	x_6	x_9	x_{17}	x_{18}

	Mode		Rate (10^8 s^{-1})	Scale factor
Γ_1	$3\pi^0$		0.0408 ± 0.0006	
Γ_2	$\pi^+\pi^-\pi^0$		0.0243 ± 0.0004	1.5
Γ_3	$\pi^\pm\mu^\mp\nu$ Called $K^0_{\mu3}$.	[a]	0.0525 ± 0.0007	1.1
Γ_6	$\pi^\pm e^\mp\nu_e$ Called K^0_{e3}.	[a]	0.0750 ± 0.0008	1.1
Γ_9	2γ		$(1.144\ \pm0.031\ )\times10^{-4}$	
Γ_{17}	$\pi^+\pi^-$		$(4.00\ \pm0.07\ )\times10^{-4}$	1.1
Γ_{18}	$\pi^0\pi^0$		$(1.81\ \pm0.04\ )\times10^{-4}$	

K_L^0 DECAY RATES

$\Gamma(3\pi^0)$ Γ_1

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.08±0.06 OUR FIT				
$\mathbf{5.22^{+1.03}_{-0.84}}$	54	BEHR 66	HLBC	Assumes *CP*

$\Gamma(\pi^+\pi^-\pi^0)$ Γ_2

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.43±0.04 OUR FIT	Error includes scale factor of 1.5.			
2.38±0.09 OUR AVERAGE				
$2.32^{+0.13}_{-0.15}$	192	BALDO-... 75	HLBC	Assumes *CP*
2.35±0.20	180	[9] JAMES 72	HBC	Assumes *CP*
2.71±0.28	99	CHO 71	DBC	Assumes *CP*
2.12±0.33	50	MEISNER 71	HBC	Assumes *CP*
2.20±0.35	53	WEBBER 70	HBC	Assumes *CP*
$2.62^{+0.28}_{-0.27}$	136	BEHR 66	HLBC	Assumes *CP*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.5 ±0.3	98	[9] JAMES 71	HBC	Assumes *CP*
3.26±0.77	18	ANDERSON 65	HBC	
1.4 ±0.4	14	FRANZINI 65	HBC	

In the fit this rate is well determined by the mean life and the branching ratio $\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)\right]$. For this reason the discrepancy between the $\Gamma(\pi^+\pi^-\pi^0)$ measurements does not affect the scale factor of the overall fit.

[9] JAMES 72 is a final measurement and includes JAMES 71.

$\Gamma(\pi^\pm\mu^\mp\nu)$ Γ_3

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*
5.25±0.07 OUR FIT	Error includes scale factor of 1.1.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$4.54^{+1.24}_{-1.08}$	19	LOWYS 67	HLBC

$\Gamma(\pi^\pm e^\mp\nu_e)$ Γ_6

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
7.50±0.08 OUR FIT	Error includes scale factor of 1.1.			
7.7 ±0.5 OUR AVERAGE				
7.81±0.56	620	CHAN 71	HBC	
$7.52^{+0.85}_{-0.72}$		AUBERT 65	HLBC	ΔS=ΔQ,*CP* assumed

$\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)$ $(\Gamma_2+\Gamma_3+\Gamma_6)$

$K_L^0 \rightarrow$ charged.

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*
15.18±0.14 OUR FIT	Error includes scale factor of 1.1.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
15.1 ±1.9	98	AUERBACH 66B	OSPK

$\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)$ $(\Gamma_3+\Gamma_6)$

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
12.75±0.12 OUR FIT	Error includes scale factor of 1.1.			
11.9 ±0.6 OUR AVERAGE	Error includes scale factor of 1.2.			
12.4 ±0.7	410	[10] BURGUN 72	HBC	$K^+p \rightarrow K^0p\pi^+$
13.1 ±1.3	252	[10] WEBBER 71	HBC	$K^-p \rightarrow n\overline{K}^0$
11.6 ±0.9	393	[10,11] CHO 70	DBC	$K^+n \rightarrow K^0p$
$9.85^{+1.15}_{-1.05}$	109	[10] FRANZINI 65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
8.47±1.69	126	[10] MANN 72	HBC	$K^-p \rightarrow n\overline{K}^0$
10.3 ±0.8	335	[11] HILL 67	DBC	$K^+n \rightarrow K^0p$

[10] Assumes $\Delta S = \Delta Q$ rule.

[11] CHO 70 includes events of HILL 67.

K_L^0 BRANCHING RATIOS

$\Gamma(3\pi^0)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.2112±0.0027 OUR FIT	Error includes scale factor of 1.1.		
0.2105±0.0028	38k	[12] KREUTZ 95	NA31

[12] KREUTZ 95 measure $3\pi^0$, $\pi^+\pi^-\pi^0$, and $\pi e\nu_e$ modes. They assume PDG 1992 values for $\pi\mu\nu_\mu$, 2π, and 2γ modes.

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_1/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.68 ±0.04 OUR FIT	Error includes scale factor of 1.3.			
1.63 ±0.05 OUR AVERAGE	Error includes scale factor of 1.4.			
1.611±0.014±0.034	38k	[13] KREUTZ 95	NA31	
1.80 ±0.13	1010	BUDAGOV 68	HLBC	
2.0 ±0.6	188	ALEKSANYAN 64B	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.65 ±0.07	883	BARMIN 72B	HLBC	Error statistical only

[13] KREUTZ 95 excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{\rm total}$ measurement, which is in the fit.

$\Gamma(3\pi^0)/\Gamma(\pi^\pm e^\mp\nu_e)$ Γ_1/Γ_6

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.545±0.009 OUR FIT	Error includes scale factor of 1.1.		
0.545±0.004±0.009	38k	[14] KREUTZ 95	NA31

[14] KREUTZ 95 measurement excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{\rm total}$ measurement, which is in the fit.

$\Gamma(3\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)\right]$ $\Gamma_1/(\Gamma_2+\Gamma_3+\Gamma_6)$

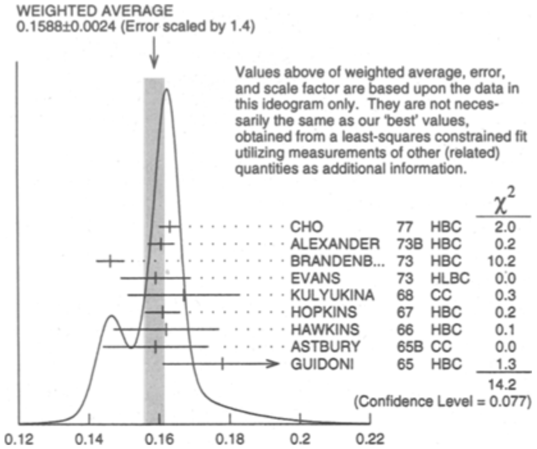
VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.269±0.004 OUR FIT	Error includes scale factor of 1.1.			
0.260±0.011 OUR AVERAGE				
0.251±0.014	549	BUDAGOV 68	HLBC	ORSAY measur.
0.277±0.021	444	BUDAGOV 68	HLBC	Ecole polytec.meas
$0.31\ ^{+0.07}_{-0.06}$	29	KULYUKINA 68	CC	
0.24 ±0.08	24	ANIKINA 64	CC	

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	*DOCUMENT ID*
0.1256±0.0020 OUR FIT	Error includes scale factor of 1.7.

$\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)\right]$ $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.1600±0.0025 OUR FIT	Error includes scale factor of 1.7.			
0.1588±0.0024 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
0.163 ±0.003	6499	CHO 77	HBC	
0.1605±0.0038	1590	ALEXANDER 73B	HBC	
0.146 ±0.004	3200	BRANDENB... 73	HBC	
0.159 ±0.010	558	EVANS 73	HLBC	
0.167 ±0.016	1402	KULYUKINA 68	CC	
0.161 ±0.005		HOPKINS 67	HBC	
0.162 ±0.015	126	HAWKINS 66	HBC	
0.159 ±0.015	326	ASTBURY 65B	CC	
0.178 ±0.017	566	GUIDONI 65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.15\ ^{+0.03}_{-0.04}$	66	ASTBURY 65	CC	
0.144 ±0.004	1729	HOPKINS 65	HBC	See HOPKINS 67
0.151 ±0.020	79	ADAIR 64	HBC	
$0.157\ ^{+0.03}_{-0.04}$	75	LUERS 64	HBC	
0.185 ±0.038	59	ASTIER 61	CC	



$\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi^\pm e^\mp\nu_e)$ Γ_2/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
0.324±0.006 OUR FIT Error includes scale factor of 1.6.				
0.336±0.003±0.007	28k	KREUTZ	95	NA31

$\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu_e)$ Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.701±0.009 OUR FIT					
0.697±0.010 OUR AVERAGE					
0.702±0.011	33k	CHO	80	HBC	
0.662±0.037	10k	WILLIAMS	74	ASPK	
0.741±0.044	6700	BRANDENB...	73	HBC	
0.662±0.030	1309	EVANS	73	HLBC	
0.71 ±0.05	770	BUDAGOV	68	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.68 ±0.08	3548	BASILE	70	OSPK	
0.71 ±0.04	569	[15] BEILLIERE	69	HLBC	
0.648±0.030	1309	EVANS	69	HLBC	Repl. by EVANS 73
0.67 ±0.13		[16] KULYUKINA	68	CC	
0.82 ±0.10		DEBOUARD	67	OSPK	
0.7 ±0.2	273	HAWKINS	67	HBC	
0.81 ±0.08		HOPKINS	67	HBC	
0.81 ±0.19		ADAIR	64	HBC	

[15] BEILLIERE 69 is a scanning experiment using same exposure as BUDAGOV 68.

[16] KULYUKINA 68 $\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu_e)$ is not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)\right]$ and $\Gamma(\pi^\pm e^\mp\nu_e)/\left[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)\right]$.

$\Gamma(\pi^\pm\mu^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.3461±0.0030 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.335 ±0.055	330	[17] KULYUKINA	68	CC
0.39 $^{+0.08}_{-0.10}$	172	[17] ASTBURY	65	CC
0.356 ±0.07	251	[17] LUERS	64	HBC

[17] This mode not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)\right]$ and $\Gamma(\pi^\pm e^\mp\nu_e)/\left[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)\right]$.

$\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_6/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.4939±0.0030 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.498 ±0.052	500	KULYUKINA	68	CC
0.46 $^{+0.08}_{-0.10}$	202	ASTBURY	65	CC
0.487 ±0.05	153	LUERS	64	HBC
0.46 ±0.11	24	NYAGU	61	CC

$\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_6/(\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.5880±0.0033 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.415 ±0.120	320	ASTIER	61	CC

$[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]/\Gamma_{\text{total}}$ $(\Gamma_3+\Gamma_6)/\Gamma$

VALUE	DOCUMENT ID
0.6596±0.0030 OUR FIT Error includes scale factor of 1.2.	

$\Gamma(2\gamma)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.92±0.15 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.54±0.84		[18] BANNER	72B	OSPK	
4.5 ±1.0	23	ENSTROM	71	OSPK	K^0_L 1.5–9 GeV/c
5.0 ±1.0		[19] REPELLIN	71	OSPK	
5.5 ±1.1	90	KUNZ	68	OSPK	Norm.to 3 π(C+N)
7.4 ±1.6	33	[20] CRONIN	67	OSPK	
6.7 ±2.2	32	TODOROFF	67	OSPK	Repl. CRIEGEE 66
1.3 ±0.6		[21] CRIEGEE	66	OSPK	

[18] This value uses $(\eta_{00}/\eta_{+-})^2 = 1.05\pm0.14$. In general, $\Gamma(2\gamma)/\Gamma_{\text{total}} = [(4.32\pm0.55)\times 10^{-4}][(\eta_{00}/\eta_{+-})^2]$.

[19] Assumes regeneration amplitude in copper at 2 GeV is 22 mb. To evaluate for a given regeneration amplitude and error, multiply by (regeneration amplitude/22mb)^2.

[20] CRONIN 67 replaced by KUNZ 68.

[21] CRIEGEE 66 replaced by TODOROFF 67.

$\Gamma(2\gamma)/\Gamma(3\pi^0)$ Γ_9/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.80±0.08 OUR FIT Error includes scale factor of 1.1.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.13±0.43	28	BARMIN	71	HLBC	
2.24±0.28	115	BANNER	69	OSPK	
2.5 ±0.7	16	ARNOLD	68B	HLBC	Vacuum decay

$\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ Γ_9/Γ_{18}

VALUE	EVTS	DOCUMENT ID		TECN
0.632±0.009 OUR FIT				
0.632±0.004±0.008	110k	BURKHARDT	87	NA31

$\Gamma(3\gamma)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN
<2.4 × 10^{-7}	90	[22] BARR	95C	NA31

[22] Assumes a phase-space decay distribution.

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.7 ±0.2 ±0.2		63	[23] BARR	92	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.86±0.60±0.60		60	PAPADIMITR...91		E731	$m_{\gamma\gamma}$ > 280 MeV
< 5.1	90		PAPADIMITR...91		E731	$m_{\gamma\gamma}$ < 264 MeV
2.1 ±0.6		14	[24] BARR	90C	NA31	$m_{\gamma\gamma}$ > 280 MeV
< 2.7	90		PAPADIMITR...89		E731	In PAPADI...91
<230	90	0	BANNER	69	OSPK	

[23] BARR 92 find that $\Gamma(\pi^0 2\gamma,\ m_{\gamma\gamma} < 240\ \text{MeV})/\Gamma(\pi^0 2\gamma) < 0.09$ (90% CL).

[24] BARR 90C superseded by BARR 92.

$\Gamma(\pi^0\pi^\pm e^\mp\nu)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN
5.18±0.29 OUR AVERAGE					
5.16±0.20±0.22		729	MAKOFF	93	E731
6.2 ±2.0		16	CARROLL	80C	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<220	90		[25] DONALDSON	74	SPEC

[25] DONALDSON 74 uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma((\pi\mu\text{atom})\nu)/\Gamma(\pi^\pm\mu^\mp\nu)$ Γ_{13}/Γ_3

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN
3.90±0.39	155	[26] ARONSON	86	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	18	COOMBES	76	WIRE

[26] ARONSON 86 quote theoretical value of $(4.31 \pm 0.08) \times 10^{-7}$.

$\Gamma(\pi^\pm e^\mp\nu_e\gamma)/\Gamma(\pi^\pm e^\mp\nu_e)$ Γ_{14}/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.934±0.036$^{+0.055}_{-0.039}$	1384	LEBER	96	NA31	$E^*_\gamma \geq$ 30 MeV, $\theta^*_{e\gamma} \geq 20°$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.3 ±2.0	10	PEACH	71	HLBC	γ KE >15 MeV

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_{15}/Γ

For earlier limits see our 1992 edition Physical Review **D45,** 1 June, Part II (1992).

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
4.61±0.14 OUR AVERAGE					
4.66±0.15	3136	[27] RAMBERG	93	E731	E_γ >20 MeV
4.41±0.32	1062	[28] CARROLL	80B	SPEC	E_γ >20 MeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.52±0.16	516	[29] CARROLL	80B	SPEC	E_γ >20 MeV
2.89±0.28	546	[30] CARROLL	80B	SPEC	
6.2 ±2.1	24	[31] DONALDSON	74C	SPEC	

[27] RAMBERG 93 finds that fraction of Direct Emission (DE) decays with E_γ >20 MeV is 0.685 ± 0.041.
[28] Both components. Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[29] Internal Bremsstrahlung component only.
[30] Direct γ emission component only.
[31] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
< 5.6			BARR	94	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<230	90	0	ROBERTS	94	E799

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	DOCUMENT ID	
2.067±0.035 OUR FIT Error includes scale factor of 1.1.		
2.107±0.055	[32] ETAFIT	98

[32] This ETAFIT value is computed from fitted values of $|\eta_{+-}|$, the K^0_L and K^0_S lifetimes, and the $K^0_S \rightarrow \pi^+\pi^-$ branching fraction. See the discussion in the note "Fits for K^0_L *CP*-Violation Parameters."

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{17}/Γ_2

Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
1.645±0.030 OUR FIT Error includes scale factor of 1.1.					
1.64 ±0.04	4200	MESSNER	73	ASPK	$\eta_{+-} = 2.23$

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_{17}/(\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.13±0.06 OUR FIT Error includes scale factor of 1.1.					
3.08±0.10 OUR AVERAGE					
3.13±0.14	1687	COUPAL	85	SPEC	η_{+-}=2.28 ± 0.06
3.04±0.14	2703	DEVOE	77	SPEC	η_{+-}=2.25 ± 0.05
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.51±0.23	309	[33] DEBOUARD	67	OSPK	η_{+-}=2.00 ± 0.09
2.35±0.19	525	[33] FITCH	67	OSPK	η_{+-}=1.94 ± 0.08

[33] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \rightarrow 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_{17}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.63 ±0.04 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.60 ±0.07	4200	[34] MESSNER	73	ASPK	η_{+-} = 2.23 ± 0.05
1.93 ±0.26		[35] BASILE	66	OSPK	η_{+-} = 1.92 ± 0.13
1.993±0.080		[35] BOTT-...	66	OSPK	η_{+-} = 1.95 ± 0.04
2.08 ±0.35	54	[35] GALBRAITH	65	OSPK	η_{+-} = 1.99 ± 0.16
2.0 ±0.4	45	[35] CHRISTENS...	64	OSPK	η_{+-} = 1.95 ± 0.20

[34] From same data as $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ MESSNER 73, but with different normalization.
[35] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \rightarrow 2\pi$ DECAY" below for average η_{+-}.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{18}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.936±0.020 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.5 ±0.8	189	[36] GAILLARD	69	OSPK	η_{00}=3.6 ± 0.6
1.2 $^{+1.5}_{-1.2}$	7	[37] CRIEGEE	66	OSPK	

[36] Latest result of this experiment given by FAISSNER 70 $\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$.
[37] CRIEGEE 66 experiment not designed to measure $2\pi^0$ decay mode.

$\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ Γ_{18}/Γ_1

Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.443±0.012 OUR FIT Error includes scale factor of 1.1.					
0.39 ±0.06 OUR AVERAGE					
0.37 ±0.08	29	BARMIN	70	HLBC	η_{00}=2.02 ± 0.23
0.32 ±0.15	30	BUDAGOV	70	HLBC	η_{00}=1.9 ± 0.5
0.46 ±0.11	57	BANNER	69	OSPK	η_{00}=2.2 ± 0.3
not seen		BARTLETT	68	OSPK	See η_{00} below
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.21 ±0.30	150	[38] REY	76	OSPK	η_{00}=3.8 ± 0.5
0.90 ±0.30	172	[39] FAISSNER	70	OSPK	η_{00}=3.2 ± 0.5
1.31 ±0.31	133	[38] CENCE	69	OSPK	η_{00}=3.7 ± 0.5
1.89 ±0.31	109	[40] CRONIN	67	OSPK	η_{00}=4.9 ± 0.5
1.36 ±0.18		[40] CRONIN	67B	OSPK	η_{00}=3.92 ± 0.3

[38] CENCE 69 events are included in REY 76.
[39] FAISSNER 70 contains same $2\pi^0$ events as GAILLARD 69 $\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$.
[40] CRONIN 67B is further analysis of CRONIN 67, now both withdrawn.

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ Γ_{18}/Γ_{17}

Violates *CP* conservation.

VALUE	DOCUMENT ID	
0.453 ±0.006 OUR FIT		
0.4535±0.0063	[41] ETAFIT	98

[41] This ETAFIT value is computed from fitted values of $|\eta_{00} / \eta_{+-}|$ and the $\Gamma(K^0_S \rightarrow \pi^+\pi^-) / \Gamma(K^0_S \rightarrow \pi^0\pi^0)$ branching fraction. See the discussion in the note "Fits for K^0_L *CP*-Violation Parameters."

$\Gamma(\mu^+\mu^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_{19}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 2.0	90	BOTT-...	67	OSPK
< 35.0	90	FITCH	67	OSPK
<250.0	90	ALFF-...	66B	OSPK
<100.0		ANIKINA	65	CC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_{19}/Γ_{17}

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.50±0.21 OUR AVERAGE Error includes scale factor of 1.4.						
3.87±0.30		179	[42] AKAGI	95	SPEC	
3.38±0.17		707	HEINSON	95	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.9 ±0.3 ±0.1		178	[43] AKAGI	91B	SPEC	In AKAGI 95
3.45±0.18±0.13		368	[44] HEINSON	91	SPEC	In HEINSON 95
4.1 ±0.5		54	INAGAKI	89	SPEC	In AKAGI 91B
2.8 ±0.3 ±0.2		87	MATHIAZHA...	89B	SPEC	In HEINSON 91
4.0 $^{+1.4}_{-0.9}$		15	SHOCHET	79	SPEC	
4.2 $^{+5.1}_{-2.6}$		3	[45] FUKUSHIMA	76	SPEC	
5.8 $^{+2.3}_{-1.5}$		9	[46] CARITHERS	73	SPEC	
< 1.53	90	0	[47] CLARK	71	SPEC	
< 18.	90	0	DARRIULAT	70	SPEC	
<140.	90	0	FOETH	69	SPEC	

[42] AKAGI 95 gives this number multiplied by the PDG 1992 average for $\Gamma(K^0_L \rightarrow \pi^+\pi^-)/\Gamma(\text{total})$.
[43] AKAGI 91B give this number multiplied by the 1990 PDG average for $\Gamma(K^0_L \rightarrow \pi^+\pi^-)/\Gamma(\text{total})$.
[44] HEINSON 91 give $\Gamma(K^0_L \rightarrow \mu\mu)/\Gamma_{\text{total}}$. We divide out the $\Gamma(K^0_L \rightarrow \pi^+\pi^-)/\Gamma_{\text{total}}$ PDG average which they used.
[45] FUKUSHIMA 76 errors are at CL = 90%.
[46] CARITHERS 73 errors are at CL = 68%, W.Carithers, (private communication 79).
[47] CLARK 71 limit raised from 1.2×10^{-6} by FIELD 74 reanalysis. Not in agreement with subsequent experiments. So not averaged.

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ Γ_{20}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN
3.25±0.28 OUR AVERAGE					
3.4 ±0.6 ±0.4		45	FANTI	97	NA48
3.23±0.23±0.19		197	SPENCER	95	E799
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.8 ±2.8		1	[48] CARROLL	80D	SPEC
<78.1	90		[49] DONALDSON	74	SPEC

[48] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[49] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{21}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.41	90	0	[50] ARISAKA	93B	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.6	90	1	AKAGI	95	SPEC	
< 1.6	90	1	AKAGI	91	SPEC	Sup. by AKAGI 95
< 5.6	90		INAGAKI	89	SPEC	In AKAGI 91
< 3.2	90		MATHIAZHA...	89	SPEC	In ARISAKA 93B
< 110	90		COUSINS	88	SPEC	
< 45	90		GREENLEE	88	SPEC	Repl. by JASTRZEMBSKI 88
< 12	90		JASTRZEM...	88	SPEC	
< 15.7	90		[51] CLARK	71	ASPK	
<1500	90	0	FOETH	69	ASPK	

[50] ARISAKA 93B includes all events with <6 MeV radiated energy.
[51] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^+e^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_{21}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*
< 23.0	90	BOTT-...	67	OSPK
< 200.0	90	ALFF-...	66B	OSPK
<1000.0		ANIKINA	65	CC

$\Gamma(e^+e^-\gamma)/\Gamma_{\rm total}$ Γ_{22}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
9.1±0.5 OUR AVERAGE					
9.2±0.5±0.5		1053	BARR	90B	NA31
$9.1\pm0.4^{+0.6}_{-0.5}$		919	OHL	90B	B845

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
17.4±8.7		4	[52] CARROLL	80D	SPEC
<27	90	0	[53] BARMIN	72	HLBC

[52] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[53] Uses $K^0_L \rightarrow 3\pi^0/\text{total} = 0.214$.

$\Gamma(e^+e^-\gamma\gamma)/\Gamma_{\rm total}$ Γ_{23}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
6.5±1.2 OUR AVERAGE					
6.5±1.2±0.6	58	NAKAYA	94	E799	$E_\gamma > 5$ MeV
6.6±3.2		MORSE	92	B845	$E_\gamma > 5$ MeV

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\rm total}$ Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< **4.6**	90		NOMURA	97	SPEC	$m_{ee} > 4$ MeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< 25	90	0	BALATS	83	SPEC
< 88.1	90		[54] DONALDSON	76	SPEC
<300			ANIKINA	73	STRC

[54] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\mu^+\mu^-e^+e^-)/\Gamma_{\rm total}$ Γ_{25}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
$\mathbf{2.9^{+6.7}_{-2.4}}$		1	GU	96	E799

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<4900	90		BALATS	83	SPEC

$\Gamma(e^+e^-e^+e^-)/\Gamma_{\rm total}$ Γ_{26}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.1 ±0.8 OUR AVERAGE	Error includes scale factor of 1.2.					
6 ±2 ±1		18	[55] AKAGI	95	SPEC	m_{ee} >470 MeV
10.4 ±3.7 ±1.1		8	[56] BARR	95	NA31	
3.96±0.78±0.32		27	GU	94	E799	
3.07±1.25±0.26		6	VAGINS	93	B845	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
7 ±3 ±2		6	[55] AKAGI	95	SPEC	m_{ee} >470 MeV
6 ±2 ±1		18	AKAGI	93	CNTR	Sup. by AKAGI 95
4 ±3		2	BARR	91	NA31	Sup. by BARR 95
<260	90		BALATS	83	SPEC	

[55] Values are for the total branching fraction, acceptance-corrected for the m_{ee} cuts shown.
[56] Distribution of angles between two e^+e^- pair planes favors $CP = -1$ for K^0_L.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\rm total}$ Γ_{27}/Γ

Violates *CP* in leading order. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< **5.1**	90	0	HARRIS	93	E799

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< 1200	90	0	[57] CARROLL	80D	SPEC
<56600	90		[58] DONALDSON	74	SPEC

[57] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[58] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\pi^0e^+e^-)/\Gamma_{\rm total}$ Γ_{28}/Γ

Violates *CP* in leading order. Direct and indirect *CP*-violating contributions are expected to be comparable and to dominate the *CP*-conserving part. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< **4.3**	90	0	HARRIS	93B	E799
< 7.5	90	0	BARKER	90	E731
< 5.5	90	0	OHL	90	B845

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< 40	90		BARR	88	NA31
< 320	90		JASTRZEM...	88	SPEC
<2300	90	0	[59] CARROLL	80D	SPEC

[59] Uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

$\Gamma(\pi^0\nu\overline{\nu})/\Gamma_{\rm total}$ Γ_{29}/Γ

Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed. Test of $\Delta S = 1$ weak neutral current.

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< **5.8**	90	0	WEAVER	94	E799

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< 22	90	0	GRAHAM	92	CNTR
<760	90		[60] LITTENBERG	89	RVUE

[60] LITTENBERG 89 is from retroactive data analysis of CRONIN 67.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\rm total}$ Γ_{30}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-11})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< **3.3**	90	0	[61] ARISAKA	93	B791	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-11})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 9.4	90	0	AKAGI	95	SPEC	
< 3.9	90	0	ARISAKA	93	B791	
< 9.4	90	0	AKAGI	91	SPEC	Sup. by AKAGI 95
< 43	90		INAGAKI	89	SPEC	In AKAGI 91
< 22	90		MATHIAZHA...	89	SPEC	
< 190	90		SCHAFFNER	89	SPEC	
<1100	90		COUSINS	88	SPEC	
< 670	90		GREENLEE	88	SPEC	Repl. by SCHAFFNER 89
< 157	90		[62] CLARK	71	ASPK	

[61] This is the combined result of ARISAKA 93 and MATHIAZHAGAN 89.
[62] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^\pm e^\pm\mu^\mp\mu^\mp)/\Gamma_{\rm total}$ Γ_{31}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<6.1	90	0	[63] GU	96	E799

[63] Assuming uniform phase space distribution.

$\Gamma(e^\pm\mu^\mp)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ $\Gamma_{30}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test of lepton family number conservation.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*
< 0.1	90	BOTT-...	67	OSPK
< 0.08	90	FITCH	67	OSPK
< 1.0	90	CARPENTER	66	OSPK
<10.0		ANIKINA	65	CC

ENERGY DEPENDENCE OF K^0_L DALITZ PLOT

For discussion, see note on Dalitz plot parameters in the $K^\pm$ section of the Particle Listings above. For definitions of a_v, a_t, a_u, and a_y, see the earlier version of the same note in the 1982 edition of this *Review* published in Physics Letters **111B** 70 (1982).

$$|\text{matrix element}|^2 = 1 + gu + hu^2 + jv + kv^2$$
where $u = (s_3 - s_0) / m^2_\pi$ and $v = (s_1 - s_2) / m^2_\pi$

LINEAR COEFFICIENT g FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.670±0.014 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
0.681±0.024	6499	CHO	77	HBC	
0.620±0.023	4709	PEACH	77	HBC	
0.677±0.010	509k	MESSNER	74	ASPK	$a_y = -0.917 \pm 0.013$

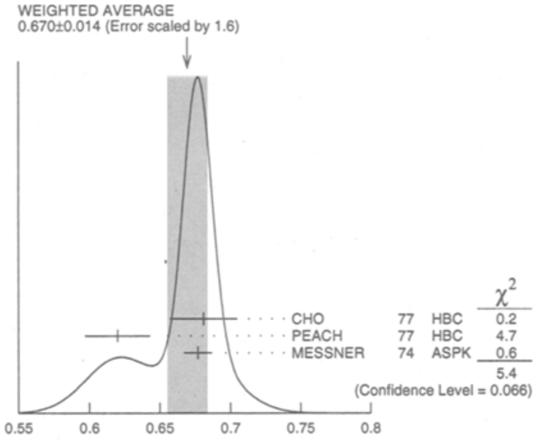
• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.69 ±0.07	192	[64] BALDO-...	75	HLBC	
0.590±0.022	56k	[64] BUCHANAN	75	SPEC	$a_u = -0.277 \pm 0.010$
0.619±0.027	20k	[64,65] BISI	74	ASPK	$a_t = -0.282 \pm 0.011$
0.612±0.032		[64] ALEXANDER	73B	HBC	
0.73 ±0.04	3200	[64] BRANDENB...	73	HBC	
0.50 ±0.11	180	[64] JAMES	72	HBC	
0.608±0.043	1486	[64] KRENZ	72	HLBC	$a_t = -0.277 \pm 0.018$
0.688±0.074	384	[64] METCALF	72	ASPK	$a_t = -0.31 \pm 0.03$
0.650±0.012	29k	[64] ALBROW	70	ASPK	$a_y = -0.858 \pm 0.015$
0.593±0.022	36k	[64,66] BUCHANAN	70	SPEC	$a_u = -0.278 \pm 0.010$
0.664±0.056	4400	[64] SMITH	70	OSPK	$a_t = -0.306 \pm 0.024$
0.400±0.045	2446	[64] BASILE	68B	OSPK	$a_t = -0.188 \pm 0.020$
0.649±0.044	1350	[64] HOPKINS	67	HBC	$a_t = -0.294 \pm 0.018$
0.428±0.055	1198	[64] NEFKENS	67	OSPK	$a_u = -0.204 \pm 0.025$
0.64 ±0.17	280	[64] ANIKINA	66	CC	$a_v = -8.2^{+0.9}_{-1.3}$
0.70 ±0.12	126	[64] HAWKINS	66	HBC	$a_v = -8.6 \pm 0.7$
0.32 ±0.13	66	[64] ASTBURY	65	CC	$a_v = -5.5 \pm 1.5$
0.51 ±0.09	310	[64] ASTBURY	65B	CC	$a_v = -7.3^{+0.6}_{-0.8}$
0.55 ±0.23	79	[64] ADAIR	64	HBC	$a_v = -7.6 \pm 1.7$
0.51 ±0.20	77	[64] LUERS	64	HBC	$a_v = -7.3 \pm 1.6$

[64] Quadratic dependence required by some experiments. (See sections on "QUADRATIC COEFFICIENT h" and "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

[65] BISI 74 value comes from quadratic fit with quad. term consistent with zero. g error is thus larger than if linear fit were used.

[66] BUCHANAN 70 result revised by BUCHANAN 75 to include radiative correlations and to use more reliable K^0_L momentum spectrum of second experiment (had same beam).



Linear coeff. g for $K^0_L \to \pi^+\pi^-\pi^0$ matrix element squared

QUADRATIC COEFFICIENT h FOR $K^0_L \to \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.079±0.007 OUR AVERAGE				
0.095±0.032	6499	CHO	77	HBC
0.048±0.036	4709	PEACH	77	HBC
0.079±0.007	509k	MESSNER	74	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.011±0.018	29k	[67] ALBROW	70	ASPK
0.043±0.052	4400	[67] SMITH	70	OSPK

See notes in section "LINEAR COEFFICIENT g FOR $K^0_L \to \pi^+\pi^-\pi^0$ |MATRIX ELEMENT$|^2$" above.

[67] Quadratic coefficients h and k required by some experiments. (See section on "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

QUADRATIC COEFFICIENT k FOR $K^0_L \to \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.0098±0.0018 OUR AVERAGE				
0.024 ±0.010	6499	CHO	77	HBC
−0.008 ±0.012	4709	PEACH	77	HBC
0.0097±0.0018	509k	MESSNER	74	ASPK

LINEAR COEFFICIENT j FOR $K^0_L \to \pi^+\pi^-\pi^0$ (CP-VIOLATING TERM)

Listed in CP-violation section below.

QUADRATIC COEFFICIENT h FOR $K^0_L \to \pi^0\pi^0\pi^0$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN
−3.3±1.1±0.7	5M	[68] SOMALWAR	92	E731

[68] SOMALWAR 92 chose m_{π^+} as normalization to make it compatible with the Particle Data Group $K^0_L \to \pi^+\pi^-\pi^0$ definitions.

K^0_L FORM FACTORS

For discussion, see note on form factors in the $K^\pm$ section of the Particle Listings above.

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.

f_S and f_T refer to the scalar and tensor term.

$f_0 = f_+ + f_- t/(m^2_K - m^2_\pi)$.

λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.

λ_+ refers to the $K^0_{\mu 3}$ value except in the K^0_{e3} sections.

$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K^0_{\mu 3}$.

$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K^0_{\mu 3}$.

t = momentum transfer to the π in units of m^2_π.

DP = Dalitz plot analysis.

PI = π spectrum analysis.

MU = μ spectrum analysis.

POL= μ polarization analysis.

BR = $K^0_{\mu 3}/K^0_{e3}$ branching ratio analysis.

E = positron or electron spectrum analysis.

RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K^0_{e3} DECAY)

For radiative correction of K^0_{e3} DP, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0300±0.0016 OUR AVERAGE		Error includes scale factor of 1.2.			
0.0306±0.0034	74k	BIRULEV	81	SPEC	DP
0.025 ±0.005	12k	[69] ENGLER	78B	HBC	DP
0.0348±0.0044	18k	HILL	78	STRC	DP
0.0312±0.0025	500k	GJESDAL	76	SPEC	DP
0.0270±0.0028	25k	BLUMENTHAL	75	SPEC	DP
0.044 ±0.006	24k	BUCHANAN	75	SPEC	DP
0.040 ±0.012	2171	WANG	74	OSPK	DP
0.045 ±0.014	5600	ALBROW	73	ASPK	DP
0.019 ±0.013	1871	BRANDENB...	73	HBC	PI transv.
0.022 ±0.014	1910	NEUHOFER	72	ASPK	PI
0.023 ±0.005	42k	BISI	71	ASPK	DP
0.05 ±0.01	16k	CHIEN	71	ASPK	DP, no RC
0.02 ±0.013	1000	ARONSON	68	OSPK	PI
+0.023 ±0.012	4800	BASILE	68	OSPK	DP, no RC
−0.01 ±0.02	762	FIRESTONE	67	HBC	DP, no RC
+0.01 ±0.015	531	KADYK	67	HBC	e,PI, no RC
$+0.08\ ^{+0.10}_{-0.08}$	240	LOWYS	67	FBC	PI
+0.15 ±0.08	577	FISHER	65	OSPK	DP, no RC
+0.07 ±0.06	153	LUERS	64	HBC	DP, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.029 ±0.005	19k	[69] CHO	80	HBC	DP
0.0286±0.0049	26k	BIRULEV	79	SPEC	Repl. by BIRULEV 81
0.032 ±0.0042	48k	BIRULEV	76	SPEC	Repl. by BIRULEV 81

[69] ENGLER 78B uses an unique K_{e3} subset of CHO 80 events and is less subject to systematic effects.

$\xi_A = f_-/f_+$ (determined from $K^0_{\mu 3}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID		TECN	COMMENT
−0.11±0.09 OUR EVALUATION			Error includes scale factor of 2.3. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.10±0.09	−12	150k	[70] BIRULEV	81	SPEC	DP
+0.26±0.16	−13	14k	[71] CHO	80	HBC	DP
+0.13±0.23	−20	16k	[71] HILL	79	STRC	DP
−0.25±0.22	−5.9	32k	[72] BUCHANAN	75	SPEC	DP
−0.11±0.07	−17	1.6M	[73] DONALDSON	74B	SPEC	DP
−1.00±0.45	−20	1385	[74] PEACH	73	HLBC	DP
−1.5 ±0.7	−28	9086	[75] ALBROW	72	ASPK	DP
+1.2 ±0.8	−18	1341	[76] CARPENTER	66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •						
+0.50±0.61	unknown	16k	[77] DALLY	72	ASPK	DP
−3.9 ±0.4		3140	[78] BASILE	70	OSPK	DP, indep of λ_+
$-0.68^{+0.12}_{-0.20}$	−26	16k	[77] CHIEN	70	ASPK	DP

[70] BIRULEV 81 error, $d\xi(0)/d\lambda_+$ calculated by us from λ_0, λ_+. $d\lambda_0/d\lambda_+ = 0$ used.

[71] HILL 79 and CHO 80 calculated by us from λ_0, λ_+, and $d\lambda_0/d\lambda_+$.

[72] BUCHANAN 75 is calculated by us from λ_0, λ_+ and $d\lambda_0/d\lambda_+$ because their appendix A value -0.20 ± 22 assumes $\xi(t)$ constant, i.e. $\lambda_- = \lambda_+$.

[73] DONALDSON 74B gives $\xi = -0.11 \pm 0.02$ not including systematics. Above error and $d\xi(0)/d\lambda_+$ were calculated by us from λ_0 and λ_+ errors (which include systematics) and $d\lambda_0/d\lambda_+$.

[74] PEACH 73 gives $\xi(0) = -0.95 \pm 0.45$ for $\lambda_+ = \lambda_- = 0.025$. The above value is for $\lambda_- = 0$. K.Peach, private communication (1974).

[75] ALBROW 72 fit has λ_- free, gets $\lambda_- = -0.030 \pm 0.060$ or $\Lambda = +0.15^{+0.17}_{-0.11}$.

[76] CARPENTER 66 $\xi(0)$ is for $\lambda_+ = 0$. $d\xi(0)/d\lambda_+$ is from figure 9.

[77] CHIEN 70 errors are statistical only. $d\xi(0)/d\lambda_+$ from figure 4. DALLY 72 is a reanalysis of CHIEN 70. The DALLY 72 result is not compatible with assumption $\lambda_- = 0$ so not included in our fit. The nonzero λ_- value and the relatively large λ_+ value found by DALLY 72 come mainly from a single low t bin (figures 1,2). The (f_+,ξ) correlation was ignored. We estimate from figure 2 that fixing $\lambda_- = 0$ would give $\xi(0) = -1.4 \pm 0.3$ and would add 10 to χ^2. $d\xi(0)/d\lambda_+$ is not given.

[78] BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$\xi_b = f_-/f_+$ (determined from $K^0_{\mu 3}/K^0_{e3}$)

The $K^0_{\mu 3}/K^0_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_b values. Instead they are obtained directly from the authors $K^0_{\mu 3}/K^0_{e3}$ branching ratio via the fitted $K^0_{\mu 3}/K^0_{e3}$ ratio $(\Gamma(\pi^\pm \mu^\mp \nu)/\Gamma(\pi^\pm e^\mp \nu_e))$. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.11±0.09 OUR EVALUATION				Error includes scale factor of 2.3. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5 ± 0.4	6700	BRANDENB... 73	HBC	BR, $\lambda_+ = 0.019 \pm 0.013$
-0.08 ± 0.25	1309	[79] EVANS 73	HLBC	BR, $\lambda_+ = 0.02$
-0.5 ± 0.5	3548	BASILE 70	OSPK	BR, $\lambda_+ = 0.02$
$+0.45 \pm 0.28$	569	BEILLIERE 69	HLBC	BR, $\lambda_+ = 0$
-0.22 ± 0.30	1309	[79] EVANS 69	HLBC	
$+0.2^{+0.8}_{-1.2}$		KULYUKINA 68	CC	BR, $\lambda_+ = 0$
$+1.1 \pm 1.1$	389	ADAIR 64	HBC	BR, $\lambda_+ = 0$
$+0.66^{+0.9}_{-1.3}$		LUERS 64	HBC	BR, $\lambda_+ = 0$

[79] EVANS 73 replaces EVANS 69.

$\xi_c = f_-/f_+$ (determined from μ polarization in $K^0_{\mu 3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+ = 0$. $d\xi/d\lambda = \xi t$. For radiative correction to μ polarization in $K^0_{\mu 3}$, see GINSBERG 73. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.11 ±0.09 OUR EVALUATION				Error includes scale factor of 2.3. Correlation is $d\xi(0)/d\lambda_+ = -14$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).
$+0.178 \pm 0.105$	207k	[80] CLARK 77	SPEC	POL, $d\xi(0)/d\lambda_+ = +0.68$
-0.385 ± 0.105	2.2M	[81] SANDWEISS 73	CNTR	POL, $d\xi(0)/d\lambda_+ = -6$
$-1.81^{+0.50}_{-0.26}$		[82] LONGO 69	CNTR	POL, $t = 3.3$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-1.6 ± 0.5	638	[83] ABRAMS 68B	OSPK	Polarization
-1.2 ± 0.5	2608	[83] AUERBACH 66B	OSPK	Polarization

[80] CLARK 77 $t = +3.80$, $d\xi(0)/d\lambda_+ = \xi(t)t = 0.178 \times 3.80 = +0.68$.

[81] SANDWEISS 73 is for $\lambda_+ = 0$ and $t = 0$.

[82] LONGO 69 $t = 3.3$ calculated from $d\xi(0)/d\lambda_+ = -6.0$ (table 1) divided by $\xi = -1.81$.

[83] t value not given.

Im(ξ) in $K^0_{\mu 3}$ DECAY (from transverse μ pol.)

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.007±0.026 OUR AVERAGE				
0.009 ± 0.030	12M	MORSE 80	CNTR	Polarization
0.35 ± 0.30	207k	[84] CLARK 77	SPEC	POL, $t=0$
-0.085 ± 0.064	2.2M	[85] SANDWEISS 73	CNTR	POL, $t=0$
-0.02 ± 0.08		LONGO 69	CNTR	POL, $t=3.3$
-0.2 ± 0.6		ABRAMS 68B	OSPK	Polarization
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012 ± 0.026		SCHMIDT 79	CNTR	Repl. by MORSE 80

[84] CLARK 77 value has additional $\xi(0)$ dependence $+0.21\mathrm{Re}[\xi(0)]$.

[85] SANDWEISS 73 value corrected from value quoted in their paper due to new value of Re(ξ). See footnote 4 of SCHMIDT 79.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^0_{\mu 3}$ DECAY)

See also the corresponding entries and notes in section "$\xi_A = f_-/f_+$" above and section "λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^0_{\mu 3}$ DECAY)" below. For radiative correction of $K^0_{\mu 3}$ Dalitz plot see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034 ±0.005 OUR EVALUATION				From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).
0.0427 ± 0.0044	150k	BIRULEV 81	SPEC	DP
0.028 ± 0.010	14k	CHO 80	HBC	DP
0.028 ± 0.011	16k	HILL 79	STRC	DP
0.046 ± 0.030	32k	BUCHANAN 75	SPEC	DP
0.030 ± 0.003	1.6M	DONALDSON 74B	SPEC	DP
0.085 ± 0.015	9086	ALBROW 72	ASPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0337 ± 0.0033	129k	DZHORD... 77	SPEC	Repl. by BIRULEV 81
0.046 ± 0.008	82k	ALBRECHT 74	WIRE	Repl. by BIRULEV 81
0.11 ± 0.04	16k	DALLY 72	ASPK	DP
0.07 ± 0.02	16k	CHIEN 70	ASPK	Repl. by DALLY 72

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^0_{\mu 3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^μ and $d\xi(0)/d\lambda_+$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	COMMENT
0.025 ±0.006 OUR EVALUATION					Error includes scale factor of 2.3. Correlation is $d\lambda_0/d\lambda_+ = -0.16$. From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).
0.0341 ± 0.0067	unknown	150k	[86] BIRULEV 81	SPEC	DP
$+0.050 \pm 0.008$	-0.11	14k	CHO 80	HBC	DP
$+0.039 \pm 0.010$	-0.67	16k	HILL 79	STRC	DP
$+0.047 \pm 0.009$	1.06	207k	[87] CLARK 77	SPEC	POL
$+0.025 \pm 0.019$	$+0.5$	32k	[88] BUCHANAN 75	SPEC	DP
$+0.019 \pm 0.004$	-0.47	1.6M	[89] DONALDSON 74B	SPEC	DP
-0.060 ± 0.038	-0.71	1385	[90] PEACH 73	HLBC	DP
-0.018 ± 0.009	$+0.49$	2.2M	[87] SANDWEISS 73	CNTR	POL
-0.043 ± 0.052	-1.39	9086	[91] ALBROW 72	ASPK	DP
$-0.140^{+0.043}_{-0.022}$	$+0.49$		[87] LONGO 69	CNTR	POL
$+0.08 \pm 0.07$	-0.54	1371	[87] CARPENTER 66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.041 ± 0.008		14k	[92] CHO 80	HBC	BR, $\lambda_+ = 0.028$
$+0.0485 \pm 0.0076$		47k	DZHORD... 77	SPEC	In BIRULEV 81
$+0.024 \pm 0.011$		82k	ALBRECHT 74	WIRE	In BIRULEV 81
$+0.06 \pm 0.03$		6700	[93] BRANDENB... 73	HBC	BR, $\lambda_+ = 0.019 \pm 0.013$
-0.067 ± 0.227	unknown	16k	[94] DALLY 72	ASPK	DP
-0.333 ± 0.034	$+1.$	3140	[95] BASILE 70	OSPK	DP

[86] BIRULEV 81 gives $d\lambda_0/d\lambda_+ = -1.5$, giving an unreasonably narrow error ellipse which dominates all other results. We use $d\lambda_0/d\lambda_+ = 0$.

[87] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[88] BUCHANAN 75 value is from their appendix A and uses only $K_{\mu 3}$ data. $d\lambda_0/d\lambda_+$ was obtained by private communication, C.Buchanan, 1976.

[89] DONALDSON 74B $d\lambda_0/d\lambda_+$ obtained from figure 18.

[90] PEACH 73 assumes $\lambda_+ = 0.025$. Calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[91] ALBROW 72 λ_0 is calculated by us from ξ_A, λ_+ and $d\xi(0)/d\lambda_+$. They give $\lambda_0 = -0.043 \pm 0.039$ for $\lambda_- = 0$. We use our larger calculated error.

[92] CHO 80 BR result not independent of their Dalitz plot result.

[93] Fit for λ_0 does not include this value but instead includes the $K_{\mu 3}/K_{e3}$ result from this experiment.

[94] DALLY 72 gives $f_0 = 1.20 \pm 0.35$, $\lambda_0 = -0.080 \pm 0.272$, $\lambda_0{}' = -0.006 \pm 0.045$, but with a different definition of λ_0. Our quoted λ_0 is his λ_0/f_0. We cannot calculate true λ_0 error without his (λ_0,f_0) correlations. See also note on DALLY 72 in section ξ_A.

[95] BASILE 70 λ_0 is for $\lambda_+ = 0$. Calculated by us from ξ_A with $d\xi(0)/d\lambda_+ = 0$. BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$|f_S/f_+|$ FOR K^0_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.04	68	25k	BLUMENTHAL 75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.095	95	18k	HILL 78	STRC	
<0.07	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<0.19	95	5600	ALBROW 73	ASPK	
<0.15	68		KULYUKINA 67	CC	

$|f_T/f_+|$ FOR K^0_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.23	68	25k	BLUMENTHAL 75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.40	95	18k	HILL 78	STRC	
<0.34	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<1.0	95	5600	ALBROW 73	ASPK	
<1.0	68		KULYUKINA 67	CC	

$|f_T/f_+|$ FOR $K^0_{\mu 3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	DOCUMENT ID	TECN
0.12±0.12	BIRULEV 81	SPEC

α_{K^*} DECAY FORM FACTOR FOR $K_L \to e^+e^-\gamma$

α_{K^*} is the constant in the model of BERGSTROM 83 which measures the relative strength of the vector-vector transition $K_L \to K^*\gamma$ with $K^* \to \rho, \omega, \phi \to \gamma^*$ and the pseudoscalar-pseudoscalar transition $K_L \to \pi, \eta, \eta' \leftrightarrow \gamma\gamma^*$.

VALUE	DOCUMENT ID	TECN
−0.28 ±0.08 OUR AVERAGE		
−0.28 ±0.13	BARR 90B	NA31
$-0.280^{+0.099}_{-0.090}$	OHL 90B	B845

DECAY FORM FACTORS FOR $K^0_L \to \pi^{\pm}\pi^0 e^{\mp}\nu_e$

Given in MAKOFF 93.

FITS FOR K^0_L CP-VIOLATION PARAMETERS

Revised April 1998 by T.G. Trippe (LBNL).

In recent years, K^0_L CP-violation experiments have improved our knowledge of CP-violation parameters and their consistency with the expectations of CPT invariance and unitarity. For definitions of K^0_L CP-violation parameters and a brief discussion of the theory, see the article "CP Violation" by L. Wolfenstein in Section 12 of this *Review*.

This note describes our two fits for the CP-violation parameters in $K^0_L \to \pi^+\pi^-$ and $\pi^0\pi^0$ decay, one for the phases ϕ_{+-} and ϕ_{00}, and another for the amplitudes $|\eta_{+-}|$ and $|\eta_{00}|$.

Fit to ϕ_{+-}, ϕ_{00}, $\Delta\phi$, Δm, and τ_S data: We perform a joint fit to the data on ϕ_{+-}, ϕ_{00}, the phase difference $\Delta\phi = \phi_{00} - \phi_{+-}$, the K^0_L-K^0_S mass difference Δm, and the K^0_S mean life τ_S, including the effects of correlations. Measurements of ϕ_{+-} and ϕ_{00} are highly correlated with Δm and τ_S. Some measurements of τ_S are correlated with Δm. The correlations are given in the footnotes of the ϕ_{+-} and ϕ_{00} sections of the K^0_L Particle Listings and the τ_S section of the K^0_S Particle listings. In editions of the Review prior to 1996, we adjusted the experimental values of ϕ_{+-} and ϕ_{00} to account for correlations with Δm and τ_S but did not include the effects of these correlations when evaluating Δm and τ_S. When a joint fit including these correlations is done, the ϕ_{+-} measurements have a strong influence on the fitted value of Δm. This is because the CERN NA31 vacuum regeneration experiments (CAROSI 90 [1] and GEWENIGER 74B [2]), the Fermilab E773/E731 regenerator experiments (SCHWINGENHEUER 95 [3] and GIBBONS 93 [4]), and the CPLEAR K^0-$\overline{K}^0$ asymmetry experiment (ADLER 95B [5]) have very different dependences of ϕ_{+-} on Δm, as can be seen from their diagonal bands in Fig. 1. The region where the ϕ_{+-} bands from these experiments cross gives a powerful measurement of Δm which decreases the fitted Δm relative to our pre-1996 average Δm and earlier measurements such as CULLEN 70 [6], GEWENIGER 74C [7], and GJESDAL 74 [8]. This decrease brings the Δm-dependent ϕ_{+-} measurements into good agreement with each other and with ϕ(superweak), where

$$\phi(\text{superweak}) = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right) = \tan^{-1}\left(\frac{2\Delta m \tau_S \tau_L}{\hbar(\tau_L - \tau_S)}\right) . \quad (1)$$

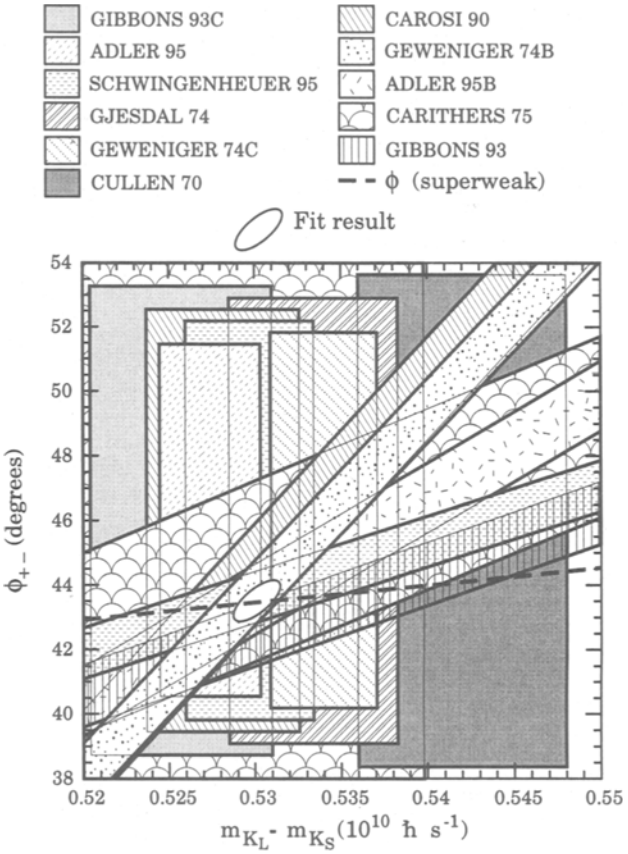


Figure 1: ϕ_{+-} vs Δm. Δm measurements appear as vertical bands spanning $\Delta m \pm 1\sigma$, some of which are cut near the top to aid the eye. The ϕ_{+-} measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows ϕ(superweak). The ellipse shows the 1σ contour of the fit result. See Table 1 for data references.

The (ϕ_{+-}, τ_S) correlations influence the τ_S fit result in a similar manner, as can be seen in Fig. 2. The influence of the ϕ_{+-} experiments is not as great on τ_S as it is on Δm because the indirect measurements of τ_S derived from the diagonal crossing bands in Fig. 2 are not as precise as the direct measurements of τ_S from E773 (SCHWINGENHEUER 95 [3]), E731 (GIBBONS 93 [4]), and NA31 (BERTANZA 97 [9]).

In Fig. 1 [Fig. 2] the slope of the diagonal ϕ_{+-} bands shows the Δm [τ_S] dependence; the unseen τ_S [Δm] dependent term is evaluated using the fitted τ_S [Δm]. The vertical half-width σ_ϕ of each band is the ϕ_{+-} error for fixed Δm [τ_S] and includes the systematic error due to the error in the fitted τ_S [Δm].

Table 2 gives the resulting fit values for the parameters and Table 3 gives the correlation matrix. The resulting ϕ_{+-} is in good agreement with ϕ(superweak) = 43.50 ± 0.08° obtained from Eq. (1) using Δm and τ_S from Table 2.

The χ^2 is 15.4 for 18 degrees of freedom, indicating good agreement of the input data. Nevertheless, there has been criticism that Fermilab E773 (SCHWINGENHEUER 95 [3]) and E731 (GIBBONS 93 [4]) measure $\phi_{+-} - \phi_f$ and calculate

Table 1: References and location of input data for Fig. 1 and Fig. 2. Unless otherwise indicated by a footnote, a check (✓) indicates that the data can be found in the ϕ_{+-} or Δm sections of the K_L Particle Listings, or the τ_S section of the K_S Particle Listings, according to the column headers.

Location of input data

Fig. 1		Fig. 2			
ϕ_{+-}	Δm	ϕ_{+-}	τ_S	PDG Document ID	Ref.
✓	✓*	✓	✓*	CAROSI 90	[1]
✓		✓†	✓	GEWENIGER 74B	[2]
✓		✓		ADLER 95B	[5]
✓	✓‡	✓†	✓	CARITHERS 75	[10]
✓	✓	✓	✓	SCHWINGENHEUER 95	[3]
✓		✓	✓	GIBBONS 93	[4]
	✓			GIBBONS 93C	[11]
	✓			ADLER 95	[12]
	✓			GJESDAL 74	[8]
	✓			GEWENIGER 74C	[7]
	✓			CULLEN 70	[6]
			✓	ARONSON 76	[13]
			✓	GROSSMAN 87	[14]
			✓	SKJEGGESTAD 72	[15]
			✓	BERTANZA 97	[9]

* from $\phi_{00}(\Delta m, \tau_S)$ in ϕ_{00} Particle Listings.

† from $\phi_{+-}(\Delta m)$ in ϕ_{+-} Particle Listings.

‡ from $\tau_S(\Delta m)$ in τ_S Particle Listings.

the regeneration phase ϕ_f from the power law momentum dependence of the regeneration amplitude using analyticity and dispersion relations. In the E731 result, a systematic error of ±0.5 degrees for departures from a pure power-law is included. For the E773 result, they modeled a variety of effects that do distort the amplitude from a pure power law and ascribed a ±0.35° systematic error from uncertainties in these effects. Even so, the E731 result remains valid within its quoted errors. KLEINKNECHT 94 [16] and KLEINKNECHT 95 [17] argue that these systematic errors should be around 3°, primarily because of the absence of data on the momentum dependence of the regeneration amplitude above 160 GeV/c. BRIERE 95 [18] and BRIERE 95C [19] reply that the current understanding of regeneration is sufficient to allow a precise and reliable correction for the region above 160 GeV/c. The question is one of judgement about the reliability of the assumptions used. In the absence of any contradictory evidence, we choose to accept the judgement of the E731/E773 experimenters in setting their systematic errors.

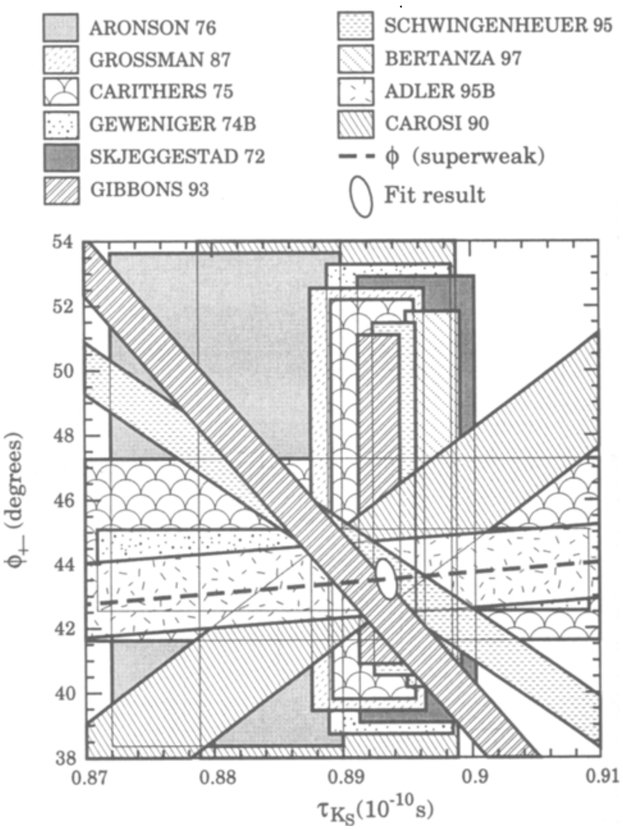


Figure 2: ϕ_{+-} vs τ_S. τ_S measurements appear as vertical bands spanning $\tau_S \pm 1\sigma$, some of which are cut near the top to aid the eye. The ϕ_{+-} measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows ϕ(superweak). The ellipse shows the fit result's 1σ contour. See Table 1 for data references.

Table 2: Results of the fit for ϕ_{+-}, ϕ_{00}, $\phi_{00} - \phi_{+-}$, Δm, and τ_S. The fit has $\chi^2 = 15.4$ for 18 degrees of freedom (22 measurements −5 parameters +1 constraint).

Quantity	Fit Result
ϕ_{+-}	$43.5 \pm 0.6°$
Δm	$(0.5301 \pm 0.0014) \times 10^{10}\hbar\ \text{s}^{-1}$
τ_S	$(0.8934 \pm 0.0008) \times 10^{-10}\text{s}$
ϕ_{00}	$43.4 \pm 1.0°$
$\Delta\phi$	$-0.1 \pm 0.8°$

A similar analysis has been done by the CPLEAR Collaboration [20]. The small differences between their results and ours are due primarily to different treatments of τ_S. Their fit constrains τ_S to the PDG 1994 value, while our fit includes the more recent SCHWINGENHEUER 95 [3] and BERTANZA 97 [9] τ_S measurements.

Table 3: Correlation matrix for the fitted parameters.

	ϕ_{+-}	Δm	τ_S	ϕ_{00}	$\Delta\phi$
ϕ_{+-}	1.00	0.72	−0.35	0.60	−0.02
Δm	0.72	1.00	−0.22	0.48	0.04
τ_S	−0.35	−0.22	1.00	−0.18	0.04
ϕ_{00}	0.60	0.48	−0.18	1.00	0.79
$\Delta\phi$	−0.02	0.04	0.04	0.79	1.00

Fit for ϵ'/ϵ, $|\eta_{+-}|$, $|\eta_{00}|$, and $\mathrm{B}(K_L \to \pi\pi)$

We list measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$ and ϵ'/ϵ. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from measurements of the K^0_L and K^0_S lifetimes (τ_L, τ_S) and branching ratios (B) to $\pi\pi$, using the relations

$$|\eta_{+-}| = \left[\frac{\mathrm{B}(K^0_L \to \pi^+\pi^-)}{\tau_L} \frac{\tau_S}{\mathrm{B}(K^0_S \to \pi^+\pi^-)}\right]^{1/2} , \qquad (2a)$$

$$|\eta_{00}| = \left[\frac{\mathrm{B}(K^0_L \to \pi^0\pi^0)}{\tau_L} \frac{\tau_S}{\mathrm{B}(K^0_S \to \pi^0\pi^0)}\right]^{1/2} . \qquad (2b)$$

For historical reasons the branching ratio fits and the *CP*-violation fits are done separately, but we want to include the influence of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and ϵ'/ϵ measurements on $\mathrm{B}(K^0_L \to \pi^+\pi^-)$ and $\mathrm{B}(K^0_L \to \pi^0\pi^0)$ and vice versa. We approximate a global fit to all of these measurements by first performing two independent fits: 1) BRFIT, a fit to the K^0_L branching ratios, rates, and mean life, and 2) ETAFIT, a fit to the $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{+-}/\eta_{00}|$, and ϵ'/ϵ measurements. The results from fit 1, along with the K^0_S values from this edition are used to compute values of $|\eta_{+-}|$ and $|\eta_{00}|$ which are included as measurements in the $|\eta_{00}|$ and $|\eta_{+-}|$ sections with a document ID of BRFIT 98. Thus the fit values of $|\eta_{+-}|$ and $|\eta_{00}|$ given in this edition include both the direct measurements and the results from the branching ratio fit.

The process is reversed in order to include the direct $|\eta|$ measurements in the branching ratio fit. The results from fit 2 above (before including BRFIT 98 values) are used along with the K^0_L and K^0_S mean lives and the $K^0_S \to \pi\pi$ branching fractions to compute the K^0_L branching ratios $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ and $\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_L \to \pi^+\pi^-)$. These branching ratio values are included as measurements in the branching ratio section with a document ID of ETAFIT 98. Thus the K^0_L branching ratio fit values in this edition include the results of direct measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and ϵ'/ϵ. A more detailed discussion of these fits is given in the 1990 edition of this *Review* [21].

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CP-VIOLATION PARAMETERS IN K^0_L DECAYS

CHARGE ASYMMETRY IN $K^0_{\ell3}$ DECAYS

Such asymmetry violates *CP*. It is related to Re(ϵ).

δ = weighted average of $\delta(\mu)$ and $\delta(e)$

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.327±0.012 OUR AVERAGE		Includes data from the 2 datablocks that follow this one.		
0.333±0.050	33M	WILLIAMS 73	ASPK	$K_{\mu3}$ + K_{e3}

$\delta(\mu) = [\Gamma(\pi^-\mu^+\nu_\mu) - \Gamma(\pi^+\mu^-\overline{\nu}_\mu)]$/SUM

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
The data in this block is included in the average printed for a previous datablock.			
0.304±0.025 OUR AVERAGE			
0.313±0.029	15M	GEWENIGER 74	ASPK
0.278±0.051	7.7M	PICCIONI 72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.60 ±0.14	4.1M	MCCARTHY 73	CNTR
0.57 ±0.17	1M	[96] PACIOTTI 69	OSPK
0.403±0.134	1M	[96] DORFAN 67	OSPK

[96] PACIOTTI 69 is a reanalysis of DORFAN 67 and is corrected for $\mu^+\mu^-$ range difference in MCCARTHY 72.

$\delta(e) = [\Gamma(\pi^-e^+\nu_e) - \Gamma(\pi^+e^-\overline{\nu}_e)]$/SUM

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
The data in this block is included in the average printed for a previous datablock.			
0.333±0.014 OUR AVERAGE			
0.341±0.018	34M	GEWENIGER 74	ASPK
0.318±0.038	40M	FITCH 73	ASPK
0.346±0.033	10M	MARX 70	CNTR
0.246±0.059	10M	[97] SAAL 69	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.36 ±0.18	600k	ASHFORD 72	ASPK
0.224±0.036	10M	[97] BENNETT 67	CNTR

[97] SAAL 69 is a reanalysis of BENNETT 67.

PARAMETERS FOR $K^0_L \to 2\pi$ DECAY

$\eta_{+-} = \mathrm{A}(K^0_L \to \pi^+\pi^-) / \mathrm{A}(K^0_S \to \pi^+\pi^-)$

$\eta_{00} = \mathrm{A}(K^0_L \to \pi^0\pi^0) / \mathrm{A}(K^0_S \to \pi^0\pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and Re(ϵ'/ϵ). Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K^0_L \to \pi\pi$ and $K^0_S \to \pi\pi$ branching ratios and the K^0_L and K^0_S lifetimes. This information is included as data in the $|\eta_{+-}|$ and $|\eta_{00}|$ sections with a Document ID "BRFIT." See the note "Fits for K^0_L *CP*-Violation Parameters" above for details.

$|\eta_{00}| = |A(K_L^0 \rightarrow 2\pi^0) / A(K_S^0 \rightarrow 2\pi^0)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.275±0.019 OUR FIT				Error includes scale factor of 1.1.
2.30 ±0.14 OUR AVERAGE				
2.25 ±0.22		[98] BRFIT 98		
2.33 ±0.18		CHRISTENS... 79	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.49 ±0.40		[99] ADLER 96B	CPLR	
2.71 ±0.37	56	[100] WOLFF 71	OSPK	Cu reg., 4γ's
2.95 ±0.63		[100] CHOLLET 70	OSPK	Cu reg., 4γ's

[98] This BRFIT value is computed from fitted values of the K_L^0 and K_S^0 lifetimes and branching fractions to $\pi\pi$. See the discussion in the note "Fits for K_L^0 *CP*-Violation Parameters."

[99] ADLER 96B identified initial neutral kaon individually as being a K^0 or a $\overline{K}^0$. Error is statistical only.

[100] CHOLLET 70 gives $|\eta_{00}|$ = (1.23 ± 0.24)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. WOLFF 71 gives $|\eta_{00}|$ = (1.13 ± 0.12)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. We compute both $|\eta_{00}|$ values for (regeneration amplitude, 2 GeV/c Cu) = 24 ± 2mb. This regeneration amplitude results from averaging over FAISSNER 69, extrapolated using optical-model calculations of Bohm et al., Physics Letters **27B** 594 (1968) and the data of BALATS 71. (From H. Faissner, private communication).

$|\eta_{+-}| = |A(K_L^0 \rightarrow \pi^+\pi^-) / A(K_S^0 \rightarrow \pi^+\pi^-)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.285±0.019 OUR FIT				
2.284±0.018 OUR AVERAGE				
2.271±0.024		[101] BRFIT 98		
2.310±0.043±0.031		[102] ADLER 95B	CPLR	K^0-$\overline{K}^0$ asymmetry
2.32 ±0.14 ±0.03	10^5	ADLER 92B	SPEC	K^0-$\overline{K}^0$ asymm.
2.27 ±0.12		CHRISTENS... 79B	ASPK	
2.30 ±0.035		GEWENIGER 74B	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.28 ±0.06	1687	[103] COUPAL 85	SPEC	$P(K)$=70 GeV/c
2.09 ±0.02		[104] ARONSON 82B	SPEC	E=30–110 GeV

[101] This BRFIT value is computed from fitted values of the K_L^0 and K_S^0 lifetimes and branching fractions to $\pi\pi$. See the discussion in the note "Fits for K_L^0 *CP*-Violation Parameters."

[102] ADLER 95B report $(2.312 \pm 0.043 \pm 0.030 - 1[\Delta m - 0.5274] + 9.1[\tau_S - 0.8926]) \times 10^{-3}$. We evaluate for our 1996 best values $\Delta m = (0.5304 \pm 0.0014) \times 10^{-10}\,\hbar s^{-1}$ and $\tau_S = (0.8927 \pm 0.0009) \times 10^{-10}$ s.

[103] COUPAL 85 concludes: no energy dependence of $|\eta_{+-}|$, because their value is consistent with above values which occur at lower energies. Not independent of COUPAL 85 $\Gamma(\pi^+\pi^-)/\Gamma(\pi \ell \nu)$ measurement. Enters $|\eta_{+-}|$ via BRFIT value. In editions prior to 1990, this measurement was erroneously also included in our $|\eta_{+-}|$ average and fit. We thank H. Wahl (WAHL 89) for informing us.

[104] ARONSON 82B find that $|\eta_{+-}|$ may depend on the kaon energy.

$|\eta_{00}/\eta_{+-}|$

VALUE	EVTS	DOCUMENT ID	TECN
0.9956±0.0023 OUR FIT Error includes scale factor of 1.8.			
0.9930±0.0020 OUR AVERAGE			
0.9931±0.0020		[105,106] BARR 93D	NA31
0.9904±0.0084±0.0036		[107] WOODS 88	E731
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.9939±0.0013±0.0015	1M	[105] BARR 93D	NA31
0.9899±0.0020±0.0025		[105] BURKHARDT 88	NA31
1.014 ±0.016 ±0.007	3152	BERNSTEIN 85B	SPEC
0.995 ±0.025	1122	BLACK 85	SPEC
1.00 ±0.09		[108] CHRISTENS... 79	ASPK
1.03 ±0.07	124	BANNER 72	OSPK
1.00 ±0.06	167	HOLDER 72	ASPK

[105] This is the square root of the ratio R given by BURKHARDT 88 and BARR 93D.

[106] This is the combined results from BARR 93D and BURKHARDT 88, taking into account a common systematic uncertainty of 0.0014.

[107] We calculate $|\eta_{00}/\eta_{+-}| = 1-3(\epsilon'/\epsilon)$ from WOODS 88 (ϵ'/ϵ) value.

[108] Not independent of $|\eta_{+-}|$ and $|\eta_{00}|$ values which are included in fit.

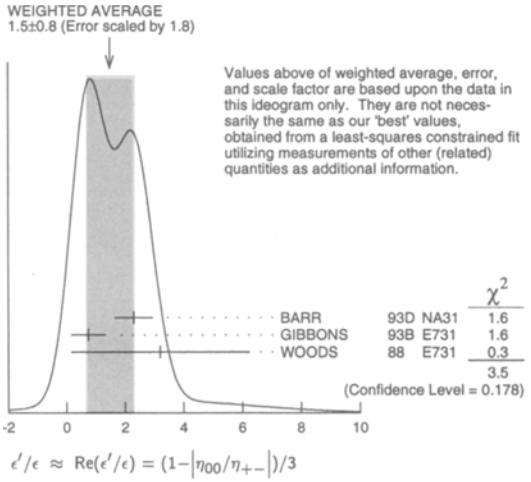
$\epsilon'/\epsilon \approx \mathrm{Re}(\epsilon'/\epsilon) = (1-|\eta_{00}/\eta_{+-}|)/3$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.5 ±0.8 OUR FIT				Error includes scale factor of 1.8.
1.5 ±0.8 OUR AVERAGE				Error includes scale factor of 1.8. See the ideogram below.
2.3 ±0.65		[109,110] BARR 93D	NA31	
0.74±0.52±0.29	>5E5	GIBBONS 93B	E731	
3.2 ±2.8 ±1.2		[109] WOODS 88	E731	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.7	1M	[111] BARR 93D	NA31	
−0.4 ±1.4 ±0.6		PATTERSON 90	E731	In GIBBONS 93B
3.3 ±1.1		[111] BURKHARDT 88	NA31	

[109] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements. They enter the average in this section but enter the fit via the $|\eta_{00}/\eta_{+-}|$ section only.

[110] This is the combined results from BARR 93D and BURKHARDT 88, taking into account their common systematic uncertainty.

[111] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements.



ϕ_{+-}, PHASE of η_{+-}

The dependence of the phase on Δm and τ_S is given for each experiment in the comments below, where Δm is the K_L^0-K_S^0 mass difference in units $10^{10}\,\hbar s^{-1}$ and τ_S is the K_S mean life in units 10^{-10} s. For the "used" data, we have evaluated these mass dependences using our 1996 values, $\Delta m = 0.5304 \pm 0.0014$, $\tau_S = 0.8927 \pm 0.0009$ to obtain the values quoted below. We also give the regeneration phase ϕ_f in the comments below.

OUR FIT is described in the note on "Fits for K_L^0 *CP*-Violation Parameters" in the K_L^0 Particle Listings.

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
43.5 ± 0.6 OUR FIT				
43.6 ± 1.2		[112] ADLER 95B	CPLR	K^0-$\overline{K}^0$ asymmetry
43.9 ± 0.8		[113,114] SCHWINGEN...95	E773	$CH_{1.1}$ regenerator
42.9 ± 1.0		[114,115] GIBBONS 93	E731	B_4C regenerator
44.3 ± 1.8		[116] CAROSI 90	NA31	Vacuum regen.
44.5 ± 2.8		[117] CARITHERS 75	SPEC	C regenerator
44.0 ± 1.3		[118] GEWENIGER 74B	ASPK	Vacuum regen.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
43.82± 0.63		[119,120] ADLER 96C	RVUE	
42.3 ± 4.4 ±1.4	10^5	[121] ADLER 92B	SPEC	K^0-$\overline{K}^0$ asymm.
47.7 ± 2.0 ±0.9		[114,122] KARLSSON 90	E731	
35.3 ± 3.9		[123] ARONSON 82B	SPEC	
41.7 ± 3.5		CHRISTENS... 79B	ASPK	
36.2 ± 6.1		[124] CARNEGIE 72	ASPK	Cu regenerator
37 ±12		[125] BALATS 71	OSPK	Cu regenerator
40 ± 4		[126] JENSEN 70	ASPK	Vacuum regen.
34 ±10		[127] BENNETT 69	CNTR	Cu regenerator
44 ±12		[128] BOHM 69B	OSPK	Vacuum regen.
45 ± 7		[129] FAISSNER 69	ASPK	Cu regenerator
51 ±11		[130] BENNETT 68B	CNTR	Cu reg. uses
70 ±21		[131] BOTT-... 67B	OSPK	C regenerator
25 ±35		[131] MISCHKE 67	OSPK	Cu regenerator
30 ±45		[131] FIRESTONE 66	HBC	
45 ±50		[131] FITCH 65	OSPK	Be regenerator

[112] ADLER 95B report $42.7° \pm 0.9° \pm 0.6° + 316[\Delta m - 0.5274]° + 30[\tau_S - 0.8926]°$.

[113] SCHWINGENHEUER 95 reports $\phi_{+-} = 43.53 \pm 0.76 + 173[\Delta m - 0.5282] - 275[\tau_S - 0.8926]$.

[114] These experiments measure $\phi_{+-}-\phi_f$ and calculate the regeneration phase from the power law momentum dependence of the regeneration amplitude using analyticity and dispersion relations. SCHWINGENHEUER 95 [GIBBONS 93] includes a systematic error of 0.35° [0.5°] for uncertainties in their modeling of the regeneration amplitude. See the discussion of these systematic errors, including criticism that they could be underestimated, in the note on "*C* violation in K_L^0 decay."

[115] GIBBONS 93 measures $\phi_{+-}-\phi_f$ and calculates the regeneration phase ϕ_f from the power law momentum dependence of the regeneration amplitude using analyticity. An error of 0.6° is included for possible uncertainties in the regeneration phase. They find $\phi_{+-} = 42.21 \pm 0.9 + 189\,[\Delta m - 0.5257] - 460\,[\tau_S - 0.8922]°$, as given in SCHWINGENHEUER 95, footnote 8. GIBBONS 93 reports ϕ_{+-} $(42.2 \pm 1.4)°$

[116] CAROSI 90 $\phi_{+-} = 46.9 \pm 1.4 \pm 0.7 + 579\,[\Delta m - 0.5351] + 303\,[\tau_S - 0.8922]°$.

[117] CARITHERS 75 $\phi_{+-} = (45.5 \pm 2.8) + 224[\Delta m - 0.5348]°$. $\phi_f = -40.9 \pm 2.6°$.

[118] GEWENIGER 74B $\phi_{+-} = (49.4 \pm 1.0) + 565[\Delta m - 0.540]°$.

[119] ADLER 96C fit gives $(43.82 \pm 0.41)° + 339(\Delta m - 0.5307)° - 252(\tau_S - 0.8922)°$.

[120] ADLER 96C is the result of a fit which includes nearly the same data as entered into the "OUR FIT" value above.

[121] ADLER 92B quote separately two systematic errors: ±0.4 from their experiment and ±1.0 degrees due to the uncertainty in the value of Δm.

[122] KARLSSON 90 systematic error does not include regeneration phase uncertainty.

[123] ARONSON 82 find that ϕ_{+-} may depend on the kaon energy.

[124] CARNEGIE 72 ϕ_{+-} is insensitive to Δm. $\phi_f = -56.2 \pm 5.2°$.

[125] BALATS 71 $\phi_{+-} = (39.0 \pm 12.0) + 198[\Delta m - 0.544]°$. $\phi_f = -43.0 \pm 4.0°$.

[126] JENSEN 70 $\phi_{+-} = (42.4 \pm 4.0) + 576[\Delta m - 0.538]°$.

[127] BENNETT 69 uses measurement of $(\phi_{+-})-(\phi_f)$ of ALFF-STEINBERGER 66B. BENNETT 69 $\phi_{+-} = (34.9 \pm 10.0)+69[\Delta m - 0.545]^\circ$. $\phi_f = -49.9 \pm 5.4^\circ$.
[128] BOHM 69B $\phi_{+-} = (41.0 \pm 12.0)+479(\Delta m - 0.526)^\circ$.
[129] FAISSNER 69 error enlarged to include error in regenerator phase. FAISSNER 69 $\phi_{+-} = (49.3 \pm 7.4)+205[\Delta m - 0.555]^\circ$. $\phi_f = -42.7 \pm 5.0^\circ$.
[130] BENNETT 69 is a re-evaluation of BENNETT 68B.
[131] Old experiments with large errors not included in average.

ϕ_{00}, PHASE OF η_{00}

See comment in ϕ_{+-} header above for treatment of Δm and τ_S dependence.

OUR FIT is described in the note on "Fits for K^0_L *CP*-Violation Parameters" in the K^0_L Particle Listings.

VALUE (°)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
43.4± 1.0 OUR FIT					
44.5± 2.5		[132] CAROSI	90	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
50.8± 7.1±1.7		[133] ADLER	96B	CPLR	
47.4± 1.4±0.9		[134] KARLSSON	90	E731	
55.7± 5.8		CHRISTENS...	79	ASPK	
38.0±25.0	56	[135] WOLFF	71	OSPK	Cu reg., 4γ's
51.0±30.0		[136] CHOLLET	70	OSPK	Cu reg., 4γ's
first quadrant preferred		GOBBI	69B	OSPK	

[132] CAROSI 90 $\phi_{00} = 47.1 \pm 2.1 \pm 1.0 +579\ [\Delta m - 0.5351] +252\ [\tau_S - 0.8922]^\circ$.
[133] ADLER 96B identified initial neutral kaon individually as being a K^0 or a $\overline{K}^0$. The systematic uncertainty is $\pm 1.5^\circ$ combined in quadrature with $\pm 0.8^\circ$ due to Δm.
[134] KARLSSON 90 systematic error does not include regeneration phase uncertainty.
[135] WOLFF 71 uses regenerator phase $\phi_f = -48.2 \pm 3.5^\circ$.
[136] CHOLLET 70 uses regenerator phase $\phi_f = -46.5 \pm 4.4^\circ$.

PHASE DIFFERENCE $\phi_{00} - \phi_{+-}$

Test of *CPT*.

OUR FIT is described in the note on "Fits for K^0_L *CP*-Violation Parameters" in the K^0_L Particle Listings.

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
− 0.1 ± 0.8 OUR FIT				
− 0.3 ± 0.8 OUR AVERAGE				
− 0.30± 0.88	[137] SCHWINGEN...	95		Combined E731, E773
0.2 ± 2.6 ±1.2	[138] CAROSI	90	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.62± 0.71±0.75	SCHWINGEN...	95	E773	
− 1.6 ± 1.2	[139] GIBBONS	93	E731	
− 0.3 ± 2.4 ±1.2	KARLSSON	90	E731	
12.6 ± 6.2	[140] CHRISTENS...	79	ASPK	
7.6 ±18.0	[141] BARBIELLINI	73	ASPK	

[137] This SCHWINGENHEUER 95 values is the combined result of SCHWINGENHEUER 95 and GIBBONS 93, accounting for correlated systematic errors.
[138] CAROSI 90 is excluded from the fit because it it is not independent of ϕ_{+-} and ϕ_{00} values.
[139] GIBBONS 93 give detailed dependence of systematic error on lifetime (see the section on the K^0_S mean life) and mass difference (see the section on $m_{K^0_L} - m_{K^0_S}$).
[140] Not independent of ϕ_{+-} and ϕ_{00} values.
[141] Independent of regenerator mechanism, Δm, and lifetimes.

CHARGE ASYMMETRY IN $\pi^+\pi^-\pi^0$ DECAYS

CHARGE ASYMMETRY J FOR $K^0_L \to \pi^+\pi^-\pi^0$

Defined at beginning of section "LINEAR COEFFICIENT g FOR $K^0_L \to \pi^+\pi^-\pi^0$ above. Such asymmetry violates *CP*. See also note on Daltitz plot parameters in $K^\pm$ section and note on *CP* violation in K^0_L decay above.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.0011±0.0008 OUR AVERAGE				
0.001 ±0.011	6499	CHO	77	
−0.001 ±0.003	4709	PEACH	77	
0.0013±0.0009	3M	SCRIBANO	70	
0.0 ±0.017	4400	SMITH	70	OSPK
0.001 ±0.004	238k	BLANPIED	68	

PARAMETERS for $K^0_L \to \pi^+\pi^-\gamma$ DECAY

$|\eta_{+-\gamma}| = |A(K^0_L \to \pi^+\pi^-\gamma, CP \text{ violating})/A(K^0_S \to \pi^+\pi^-\gamma)|$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*
2.35 ±0.07 OUR AVERAGE				
2.359±0.062±0.040	9045	MATTHEWS	95	E773
2.15 ±0.26 ±0.20	3671	RAMBERG	93B	E731

$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$

VALUE (°)	*EVTS*	*DOCUMENT ID*		*TECN*
44 ± 4 OUR AVERAGE				
43.8± 3.5± 1.9	9045	MATTHEWS	95	E773
72 ±23 ±17	3671	RAMBERG	93B	E731

$|\epsilon'_{+-\gamma}|/\epsilon$ for $K^0_L \to \pi^+\pi^-\gamma$

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<0.3	90	3671	[142] RAMBERG	93B	E731

[142] RAMBERG 93B limit on $|\epsilon'_{+-\gamma}|/\epsilon$ assumes than any difference between η_{+-} and $\eta_{+-\gamma}$ is due to direct *CP* violation.

$\Delta S = \Delta Q$ IN K^0 DECAYS

The relative amount of $\Delta S \neq \Delta Q$ component present is measured by the parameter x, defined as

$$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) .$$

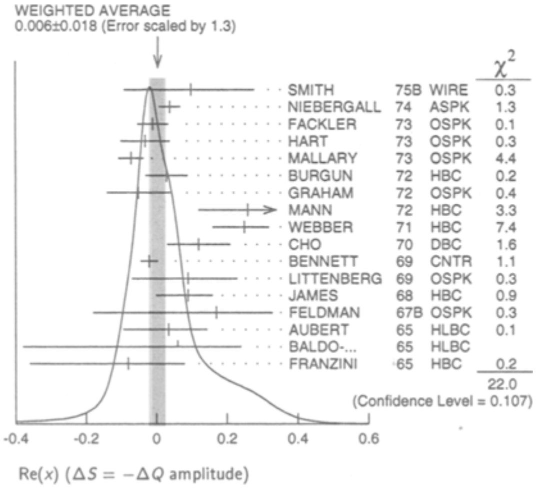
We list Re$\{x\}$ and Im$\{x\}$ for K_{e3} and $K_{\mu3}$ combined.

$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) = A(\Delta S{=}{-}\Delta Q)/A(\Delta S{=}\Delta Q)$

REAL PART OF x

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.006±0.018 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
$0.10^{+0.18}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \to K^0 \Lambda$
0.04 ±0.03	4724	NIEBERGALL	74	ASPK	$K^+ p \to K^0 p \pi^+$
−0.008±0.044	1757	FACKLER	73	OSPK	K_{e3} from K^0
−0.03 ±0.07	1367	HART	73	OSPK	K_{e3} from $K^0 \Lambda$
−0.070±0.036	1079	MALLARY	73	OSPK	K_{e3} from $K^0 \Lambda X$
0.03 ±0.06	410	[143] BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
−0.05 ±0.09	442	[144] GRAHAM	72	OSPK	$\pi^- p \to K^0 \Lambda$
$0.26^{+0.10}_{-0.14}$	126	MANN	72	HBC	$K^- p \to n \overline{K}^0$
$0.25^{+0.07}_{-0.09}$	252	WEBBER	71	HBC	$K^- p \to n \overline{K}^0$
0.12 ±0.09	215	[145] CHO	70	DBC	$K^+ d \to K^0 p p$
−0.020±0.025		[146] BENNETT	69	CNTR	Charge asym+ Cu regen.
$0.09^{+0.14}_{-0.16}$	686	LITTENBERG	69	OSPK	$K^+ n \to K^0 p$
$0.09^{+0.07}_{-0.09}$	121	JAMES	68	HBC	$\overline{p} p$
$0.17^{+0.16}_{-0.35}$	116	FELDMAN	67B	OSPK	$\pi^- p \to K^0 \Lambda$
$0.035^{+0.11}_{-0.13}$	196	AUBERT	65	HLBC	K^+ charge exchange
$0.06^{+0.18}_{-0.44}$	152	[147] BALDO-...	65	HLBC	K^+ charge exchange
$-0.08^{+0.16}_{-0.28}$	109	[148] FRANZINI	65	HBC	$\overline{p} p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.04^{+0.10}_{-0.13}$	100	[144] GRAHAM	72	OSPK	$K_{\mu3}$ from $K^0 \Lambda$
−0.13 ±0.11	342	[144] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
$0.04^{+0.07}_{-0.08}$	222	[143] BURGUN	71	HBC	$K^+ p \to K^0 p \pi^+$
0.03 ±0.03		[146] BENNETT	68	CNTR	
0.17 ±0.10	335	[145] HILL	67	DBC	$K^+ d \to K^0 p p$

[143] BURGUN 72 is a final result which includes BURGUN 71.
[144] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[145] CHO 70 is analysis of unambiguous events in new data and HILL 67.
[146] BENNETT 69 is a reanalysis of BENNETT 68.
[147] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).
[148] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.



IMAGINARY PART OF x

Assumes $m_{K^0_L} - m_{K^0_S}$ positive. See Listings above.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.003 ± 0.026 OUR AVERAGE	Error includes scale factor of 1.2.				
$-0.10^{+0.16}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \to K^0 \Lambda$
-0.06 ± 0.05	4724	NIEBERGALL	74	ASPK	$K^+ p \to K^0 p \pi^+$
-0.017 ± 0.060	1757	FACKLER	73	OSPK	K_{e3} from K^0
0.09 ± 0.07	1367	HART	73	OSPK	K_{e3} from $K^0 \Lambda$
$0.107^{+0.092}_{-0.074}$	1079	MALLARY	73	OSPK	K_{e3} from $K^0 \Lambda X$
$0.07^{+0.06}_{-0.07}$	410	[149] BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
0.05 ± 0.13	442	[150] GRAHAM	72	OSPK	$\pi^- p \to K^0 \Lambda$
$0.21^{+0.15}_{-0.12}$	126	MANN	72	HBC	$K^- p \to n \overline{K}^0$
0.0 ± 0.08	252	WEBBER	71	HBC	$K^- p \to n \overline{K}^0$
-0.08 ± 0.07	215	[151] CHO	70	DBC	$K^+ d \to K^0 p p$
$-0.11^{+0.10}_{-0.11}$	686	LITTENBERG	69	OSPK	$K^+ n \to K^0 p$
$+0.22^{+0.37}_{-0.29}$	121	JAMES	68	HBC	$\overline{p} p$
0.0 ± 0.25	116	FELDMAN	67B	OSPK	$\pi^- p \to K^0 \Lambda$
$-0.21^{+0.11}_{-0.15}$	196	AUBERT	65	HLBC	K^+ charge exchange
$-0.44^{+0.32}_{-0.19}$	152	[152] BALDO-...	65	HLBC	K^+ charge exchange
$+0.24^{+0.40}_{-0.30}$	109	[153] FRANZINI	65	HBC	$\overline{p} p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.12^{+0.17}_{-0.16}$	100	[150] GRAHAM	72	OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
-0.04 ± 0.16	342	[150] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
$0.12^{+0.08}_{-0.09}$	222	[149] BURGUN	71	HBC	$K^+ p \to K^0 p \pi^+$
-0.20 ± 0.10	335	[151] HILL	67	DBC	$K^+ d \to K^0 p p$

[149] BURGUN 72 is a final result which includes BURGUN 71.

[150] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.

[151] Footnote 10 of HILL 67 should read +0.58, not −0.58 (private communication) CHO 70 is analysis of unambiguous events in new data and HILL 67.

[152] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).

[153] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

CPT-VIOLATION PARAMETERS IN K^0 DECAY

If *CP*-violating interactions include a *T* conserving part then

$$|K_S\rangle = [|K_1\rangle + (\epsilon + \Delta)|K_2\rangle]/\sqrt{1+|\epsilon+\Delta|^2}$$
$$|K_L\rangle = [|K_2\rangle + (\epsilon - \Delta)|K_1\rangle]/\sqrt{1+|\epsilon-\Delta|^2}$$

where

$$|K_1\rangle = [|K^0\rangle + |\overline{K}^0\rangle]/\sqrt{2}$$
$$|K_2\rangle = [|K^0\rangle - |\overline{K}^0\rangle]/\sqrt{2}$$

and

$$|\overline{K}^0\rangle = CP|K^0\rangle.$$

The parameter Δ specifies the *CPT*-violating part.

Estimates of Δ are given below. See also THOMSON 95 for a test of *CPT*-symmetry conservation in K^0 decays using the Bell-Steinberger relation.

REAL PART OF Δ

A nonzero value violates *CPT* invariance.

VALUE	EVTS	DOCUMENT ID		COMMENT
0.018 ± 0.020	6481	[154] DEMIDOV	95	$K_{\ell 3}$ reanalysis

[154] DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.

IMAGINARY PART OF Δ

A nonzero value violates *CPT* invariance.

VALUE	EVTS	DOCUMENT ID		COMMENT
0.021 ± 0.037	6481	[155] DEMIDOV	95	$K_{\ell 3}$ reanalysis

[155] DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.

K^0_L REFERENCES

BRFIT	98	RPP		
ETAFIT	98	RPP		
FANTI	97	ZPHY C76 653	V. Fanti+	(NA48 Collab.)
NOMURA	97	PL B408 445	T. Nomura+	(KYOT, KEK, HIRO)
ADLER	96B	ZPHY C70 211	+Alhalel, Angelopoulos+	(CPLEAR Collab.)
ADLER	96C	PL B369 367	+Angelopoulos+	(CPLEAR Collab.)
GU	96	PRL 76 4312	+	(RUTG, UCLA, EFI, COLO, ELMT, FNAL, ILL, OSAK)
LEBER	96	PL B369 69	+Beier+	(MANZ, CERN, EDIN, ORSAY, PISA)
ADLER	95	PL B363 237	+Alhalel, Angelopoulos, Apostolakis+	(CPLEAR Collab.)
ADLER	95B	PL B363 243	+Alhalel, Angelopoulos, Apostolakis+	(CPLEAR Collab.)
AKAGI	95	PR D51 2061	+Fukuhisa, Hemmi+	(TOHOK, TOKY, KYOT, KEK)
BARR	95	ZPHY C65 361	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR	95C	PL B358 399	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
DEMIDOV	95	PAN 58 968	+Gusev, Shabalin	(ITEP)
From YAF 58 1041.				
HEINSON	95	PR D51 985	+Horvath, Knibbe, Mathiazhagan+	(BNL E791 Collab.)
KREUTZ	95	ZPHY C65 67	+Holder, Rost+	(SIEG, EDIN, MANZ, ORSAY, PISAI)
MATTHEWS	95	PRL 75 2803	+Gu, Haas, Hogan+	(RUTG, EFI, ELMT, FNAL, ILL)
SCHWINGEN...	95	PRL 74 4376	Schwingenheuer+	(EFI, CHIC, ELMT, FNAL, ILL, RUTG)
SPENCER	95	PRL 74 3323	+	(UCLA, EFI, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
THOMSON	95	PR D51 1412	+Zou	(RUTG)
BARR	94	PL B328 528	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
GU	94	PRL 72 3000	+	(RUTG, UCLA, EFI, COLO, ELMT, FNAL, ILL, OSAK)
NAKAYA	94	PRL 73 2169	+	(OSAK, UCLA, EFI, COLU, ELMT, FNAL, ILL, RUTG)
ROBERTS	94	PR D50 1874	+	(UCLA, EFI, COLU, ELMT, FNAL, ILL, OSAK, RUTG)
WEAVER	94	PRL 72 3758	+	(UCLA, EFI, COLU, ELMT, FNAL, ILL, OSAK, RUTG)
AKAGI	93	PR D47 R2644	+Fukuhisa, Hemmi+	(TOHOK, TOKY, KYOT, KEK)
ARISAKA	93	PRL 70 1049	+Auerbach, Axelrod, Belz, Biery+	(BNL E791 Collab.)
ARISAKA	93B	PRL 71 3910	+Auerbach, Axelrod, Belz, Biery+	(BNL E791 Collab.)
BARR	93D	PL B317 233	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
GIBBONS	93	PRL 70 1199	+Barker, Briere, Makoff+	(FNAL E731 Collab.)
Also	97	PR D55 6625	L.K. Gibbons+	(FNAL E731 Collab.)
GIBBONS	93B	PRL 70 1203	+Barker, Briere, Makoff+	(FNAL E731 Collab.)
GIBBONS	93C	Thesis RX-1487		(CHIC)
Also	97	PR D55 6625	L.K. Gibbons+	(FNAL E731 Collab.)
HARRIS	93	PRL 71 3914	+	(EFI, UCLA, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
HARRIS	93B	PRL 71 3918	+	(EFI, UCLA, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
MAKOFF	93	PRL 70 1591	+Barker, Briere, Gibbons+	(FNAL E731 Collab.)
Also	95	PRL 75 2069 (erratum)		
RAMBERG	93	PRL 70 2525	+Bock, Coleman, Enagonio, Hsiung+	(FNAL E731 Collab.)
RAMBERG	93B	PRL 70 2529	+Bock, Coleman, Enagonio, Hsiung+	(FNAL E731 Collab.)
VAGINS	93	PRL 71 35	+Adair, Greenlee, Kasha, Mannelli+	(BNL E845 Collab.)
ADLER	92B	PL B286 180	+Alhalel, Angelopoulos, Apostolakis+	(CPLEAR Collab.)
Also	92	SJNP 55 840	Adler, Alhalel, Angelopoulos+	(CPLEAR Collab.)
BARR	92	PL B284 440	+Buchholz+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
GRAHAM	92	PL B295 169	+Barker, Briere, Gibbons, Makoff+	(FNAL E731 Collab.)
MORSE	92	PR D45 36	+Leipuner, Larsen, Jastrzembski+	(BNL, YALE, VASS)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
SOMALWAR	92	PRL 68 2580	+Barker, Briere, Gibbons+	(FNAL E731 Collab.)
AKAGI	91	PRL 67 2614	+Fukuhisa, Hemmi+	(TOHOK, TOKY, KYOT, KEK)
AKAGI	91B	PRL 67 2618	+Fukuhisa, Hemmi+	(TOHOK, TOKY, KYOT, KEK)
BARR	91	PL B259 389	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
HEINSON	91	PR D44 R1	+	(UCI, UCLA, LANL, PENN, STAN, TEMP, TEXA+)
PAPADIMITR...	91	PR D44 R573	Papadimitriou, Barker, Briere+	(FNAL E731 Collab.)
BARKER	90	PR D41 3546	+Briere, Gibbons, Makoff+	(FNAL E731 Collab.)
Also	88	PRL 61 2661	Gibbons, Papadimitriou+	(FNAL E731 Collab.)
BARR	90B	PL B240 283	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR	90C	PL B242 523	+Carosi+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
CAROSI	90	PL B237 303	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
KARLSSON	90	PRL 64 2976	+Gollin, Okamitsu, Tschirhart, Barker+	(FNAL E731 Collab.)
OHL	90	PRL 64 2755	+Adair, Greenlee, Kasha, Mannelli+	(BNL E845 Collab.)
OHL	90B	PRL 65 1407	+Adair, Greenlee, Kasha, Mannelli+	(BNL E845 Collab.)
PATTERSON	90	PRL 64 1491	+Barker+	(FNAL E731 Collab.)
INAGAKI	89	PR D40 1712	+Kobayashi, Sato, Shinkawa+	(KEK, TOKY, KYOT)
LITTENBERG	89	PR D39 3322		(BNL)
MATHIAZHA...	89	PRL 63 2181	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
MATHIAZHA...	89B	PRL 63 2185	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
PAPADIMITR...	89	PRL 63 28	Papadimitriou, Gibbons, Patterson+	(FNAL E731 Collab.)
SCHAFFNER	89	PR D39 990	+Greenlee, Kasha, Mannelli, Ohl+	(YALE, BNL)
WAHL	89	CERN-EP/89-86, H. Wahl — Rare Decay Symposium, Vancouver		(CERN)
BARR	88	PL B214 303	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
BURKHARDT	88	PL B206 169	+Clarke+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
COUSINS	88	PR D38 2914	+Konigsberg+	(UCLA, LASL, PENN, STAN, TEMP, WILL)
GREENLEE	88	PRL 60 893	+Kasha, Mannelli, Mannelli+	(YALE, BNL)
JASTRZEM...	88	PRL 61 2300	Jastrzembski, Larsen, Leipuner, Morse+	(BNL, YALE)
WOODS	88	PRL 60 1695	+Nishikawa, Patterson, Wah, Winstein+	(FNAL E731 Collab.)
BURKHARDT	87	PL B199 139	+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
ARONSON	86	PR D33 3180	+Bernstein, Bock+	(BNL, CHIC, STAN, WISC)
Also	82	PRL 48 1078	Aronson, Bernstein+	(BNL, CHIC, STAN, WISC)
PDG	86C	PL 170B 132	Aguilar-Benitez, Porter+	(CERN, CIT+)
BERNSTEIN	85B	PRL 54 1631	+Bock, Carlsmith, Coupal+	(CHIC, SACL)
BLACK	85	PRL 54 1628	+Blatt, Campbell, Kasha, Mannelli+	(BNL, YALE)
COUPAL	85	PRL 55 566	+Bernstein, Bock, Carlsmith+	(CHIC, SACL)
BALATS	83	SJNP 38 556	+Berezin, Bogdanov, Vishnevsky+	(ITEP)
		Translated from YAF 38 927.		
BERGSTROM	83	PL 131B 229	+Masso, Singer	(CERN)
ARONSON	82	PRL 48 1078	+Bernstein+	(BNL, CHIC, STAN, WISC)
ARONSON	82B	PRL 48 1306	+Bock, Cheng, Fischbach	(BNL, CHIC, PURD)
Also	82B	PL 116B 73	Fischbach, Cheng+	(PURD, BNL, CHIC)
Also	83	PR D28 476	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
Also	83B	PR D28 495	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
PDG	82B	PL 111B 70	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
BIRULEV	81	NP B182 1	+Dzhordzhadze, Genchev, Grigalashvili+	(JINR)
Also	80	SJNP 31 622	Birulev, Vestergombi, Genchev+	(JINR)
		Translated from YAF 31 1204.		
CARROLL	80B	PRL 44 529	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80C	PL 96B 407	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80D	PRL 44 525	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CHO	80	PR D22 2688	+Derrick, Miller, Schlereth, Engler+	(ANL, CMU)
MORSE	80	PR D21 1750	+Leipuner, Larsen, Schmidt, Blatt+	(BNL, YALE)
BIRULEV	79	SJNP 29 778	+Vestergombi, Gvakhariya, Genchev+	(JINR)
		Translated from YAF 29 1516.		
CHRISTENS...	79	PRL 43 1209	Christenson, Goldman, Hummel, Roth+	(NYU)
CHRISTENS...	79B	PRL 43 1212	Christenson, Goldman, Hummel, Roth+	(NYU)
HILL	79	NP B153 39	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
SCHMIDT	79	PRL 43 556	+Blatt, Campbell, Grannan+	(YALE, BNL)
SHOCHET	79	PR D19 1965	+Linsay, Grosso-Pilcher, Frisch+	(EFI, ANL)
Also	77	PRL 39 59	Shochet, Linsay, Grosso-Pilcher+	(EFI, ANL)
ENGLER	78B	PR D18 623	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
HILL	78	PL 73B 483	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
CHO	77	PR D15 587	+Derrick, Lissauer, Miller, Engler+	(ANL, CMU)
CLARK	77	PR D15 553	+Field, Holley, Johnson, Kerth, Sah, Shen	(LBL)
Also	75	Thesis LBL-4275	Shen	(LBL)
DEVOE	77	PR D16 565	+Cronin, Frisch, Grosso-Pilcher+	(EFI, ANL)
DZHORD...	77	SJNP 26 478	Dzhordzhadze, Kekelidze, Krivokhizhin+	(JINR)
		Translated from YAF 26 910.		
PEACH	77	NP B127 399	+Cameron+	(BGNA, EDIN, GLAS, PISA, RHEL)
BIRULEV	76	SJNP 24 178	+Vestergombi, Vovenko, Votruba+	(JINR)
		Translated from YAF 24 340.		
COOMBES	76	PRL 37 249	+Flexer, Hall, Kennelly, Kirkby+	(STAN, NYU)
DONALDSON	76	PR D14 2839	+Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
Also	74	Thesis SLAC-0184	Donaldson	(SLAC)
FUKUSHIMA	76	PRL 36 348	+Jensen, Surko, Thaler+	(PRIN, MASA)
GJESDAL	76	NP B109 118	+Kamae, Presser, Steffen+	(CERN, HEIDH)
REY	76	PR D13 1161	+Cence, Jones, Parker+	(NDAM, HAWA, LBL)
Also	69	PRL 22 1210	Cence, Jones, Peterson, Stenger+	(HAWA, LRL)
BALDO-...	75	NC 25A 688	Baldo-Ceolin, Bobisut, Calimani+	(PADO, WISC)
BLUMENTHAL	75	PRL 34 164	+Frankel, Nagy+	(PENN, CHIC, TEMP)
BUCHANAN	75	PR D11 457	+Drickey, Pepper, Rudnick+	(UCLA, SLAC, JHU)
CARITHERS	75	PRL 34 1244	+Modis, Nygren, Pun+	(COLU, NYU)
SMITH	75B	Thesis UCSD unpub.		(UCSD)
ALBRECHT	74	PL 48B 393		(JINR, BERL, BUDA, PRAG, SERP, SOFI)
BISI	74	PL 50B 504	+Ferrero	(TORI)
DONALDSON	74	Thesis SLAC-0184		(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
DONALDSON	74B	PR D9 2960	+Fryberger, Hitlin, Liu+	(SLAC, UCSC)
Also	73B	PRL 31 337	Donaldson, Fryberger, Hitlin, Liu+	(SLAC, UCSC)
DONALDSON	74C	PRL 33 554	+Hitlin, Kennelly, Kirkby+	(SLAC)
Also	74	Thesis SLAC-0184	Donaldson	(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
FIELD	74	SLAC-PUB-1498 unpub.		(SLAC)
GEWENIGER	74	PL 48B 483	+Gjesdal, Kamae, Presser+	(CERN, HEIDH)
Also	74	Thesis CERN Int. 74-4	Luth	(CERN)

GEWENIGER	74B	PL 48B 487	+Gjesdal, Presser+	(CERN, HEIDH)
Also	74B	PL 52B 119	Gjesdal, Presser, Steffen+	(CERN, HEIDH)
GEWENIGER	74C	PL 52B 108	+Gjesdal, Presser+	(CERN, HEIDH)
GJESDAL	74	PL 52B 113	+Presser, Kamae, Steffen+	(CERN, HEIDH)
MESSNER	74	PRL 33 1458	+Franklin, Morse+	(COLO, SLAC, UCSC)
NIEBERGALL	74	PL 49B 103	+Regler, Stier+	(CERN, ORSAY, VIEN)
WANG	74	PR D9 540	+Smith, Whatley, Zorn, Hornbostel	(UMD, BNL)
WILLIAMS	74	PRL 33 240	+Larsen, Leipuner, Sapp, Sessoms+	(BNL, YALE)
ALBROW	73	NP B58 22	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ALEXANDER	73B	NP B65 301	+Benary, Borowitz, Lande+	(TELA, HEID)
ANIKINA	73	JINR P1 7539	+Balashov, Bannik+	(JINR)
BARBIELLINI	73	PL 43B 529	+Darriulat, Fainberg+	(CERN)
BRANDENB...	73	PR D8 1978	Brandenburg, Johnson, Leith, Loos+	(SLAC)
CARITHERS	73	PRL 31 1025	+Nygren, Gordon+	(COLU, BNL, CERN)
Also	73B	PRL 30 1336	Carithers, Modis, Nygren+	(COLU, CERN, NYU)
EVANS	73	PR D7 36	+Muir, Peach, Budagov+	(EDIN, CERN)
Also	69	PRL 23 427	Evans, Golden, Muir, Peach+	(EDIN, CERN)
FACKLER	73	PRL 31 847	+Frisch, Martin, Smoot, Sompayrac	(MIT)
FITCH	73	PRL 31 1524	+Hepp, Jensen, Strovink, Webb	(PRIN)
Also	72	Thesis COO-3072-13	Webb	(PRIN)
GINSBERG	73	PR D8 3887	+Smith	(MIT, STON)
HART	73	NP B66 317	+Hutton, Field, Sharp, Blackmore+	(CAVE, RHEL)
MALLARY	73	PR D7 1953	+Binnie, Gallivan, Gomez, Peck, Sciulli+	(CIT)
Also	70	PRL 25 1214	Sciulli, Gallivan, Binnie, Gomez+	(CIT)
MCCARTHY	73	PR D7 687	+Brewer, Budnitz, Entis, Graven, Miller+	(LBL)
Also	72	PL 42B 291	McCarthy, Brewer, Budnitz, Entis, Graven+	(LBL)
Also	71	Thesis LBL-550	McCarthy	(LBL)
MESSNER	73	PRL 30 876	+Morse, Nauenberg, Hitlin+	(COLO, SLAC, UCSC)
PEACH	73	PL 43B 441	+Evans, Muir, Hopkins, Krenz	(EDIN, CERN, AACH)
SANDWEISS	73	PRL 30 1002	+Sunderland, Turner, Willis, Keller	(YALE, ANL)
WILLIAMS	73	PRL 31 1521	+Larsen, Leipuner, Sapp, Sessoms+	(BNL, YALE)
ALBROW	72	NP B44 1	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ASHFORD	72	PL 38B 47	+Brown, Masek, Maung, Miller, Ruderman+	(UCSD)
BANNER	72	PRL 28 1597	+Cronin, Hoffman, Knapp, Shochet	(PRIN)
BANNER	72B	PRL 29 237	+Cronin, Hoffman, Knapp, Shochet	(PRIN)
BARMIN	72	SJNP 15 636	+Davidenko, Demidov, Dolgolenko+	(ITEP)
		Translated from YAF 15 1149.		
BARMIN	72B	SJNP 15 638	+Barylov, Davidenko, Demidov+	(ITEP)
		Translated from YAF 15 1152.		
BURGUN	72	NP B50 194	+Lesquoy, Muller, Pauli+	(SACL, CERN, OSLO)
CARNEGIE	72	PR D6 2335	+Cester, Fitch, Strovink, Sulak	(PRIN)
DALLY	72	PL 41B 647	+Innocenti, Seppi+	(SLAC, JHU, UCLA)
Also	70	PL 33B 627	Chien, Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	71	PL 35B 261	Chien, Cox, Ettlinger+	(JHU, SLAC, UCLA)
GRAHAM	72	NC 9A 166	+Abashian, Jones, Mantsch, Orr+	(ILL, NEAS)
HOLDER	72	PL 40B 141	+Radermacher, Staude+	(AACH, CERN, TORI)
JAMES	72	NP B49 1	+Montanet, Paul, Saetre+	(CERN, SACL, OSLO)
KRENZ	72	LNC 4 213	+Hopkins, Evans, Muir, Peach	(AACH, CERN, EDIN)
MANN	72	PR D6 137	+Kofler, Meisner, Hertzbach+	(MASA, BNL, YALE)
MANTSCH	72	NC 9A 160	+Abashian, Graham, Jones, Orr+	(ILL, NEAS)
MCCARTHY	72	PL 42B 291	+Brewer, Budnitz, Entis, Graven+	(LBL)
METCALF	72	PL 40B 703	+Neuhofer, Niebergall+	(CERN, IPN, WIEN)
NEUHOFER	72	PL 41B 642	+Niebergall, Regler, Stier+	(CERN, ORSAY, VIEN)
PICCIONI	72	PRL 29 1412	+Coombes, Donaldson, Dorfan, Fryberger+	(SLAC)
Also	74	PR D9 2939	Piccioni, Donaldson+	(SLAC, UCSC, COLO)
VOSBURGH	72	PR D6 1834	+Devlin, Esterling, Goz, Bryman+	(RUTG, MASA)
Also	71	PRL 26 866	Vosburgh, Devlin, Esterling, Goz+	(RUTG, MASA)
BALATS	71	SJNP 13 53	+Berezin, Vishnevsky, Galanina+	(ITEP)
		Translated from YAF 13 93.		
BARMIN	71	PL 35B 604	+Barylov, Veselovsky, Davidenko+	(ITEP)
BISI	71	PL 36B 533	+Darriulat, Ferrero, Rubbia+	(AACH, CERN, TORI)
BURGUN	71	LNC 2 1169	+Lesquoy, Muller, Pauli+	(SACL, CERN, OSLO)
CARNEGIE	71	PR D4 1	+Cester, Fitch, Strovink, Sulak	(PRIN)
CHAN	71	Thesis LBL-350		(LBL)
CHIEN	71	PL 35B 261	+Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	72	PL 41B 647	Dally, Innocenti, Seppi+	(SLAC, JHU, UCLA)
CHO	71	PR D3 1557	+Dralle, Canter, Engler, Fisk+	(CMU, BNL, CASE)
CLARK	71	PRL 26 1667	+Elioff, Field, Frisch, Johnson, Kerth+	(LRL)
Also	70	Thesis UCRL 19709	Johnson	(LRL)
Also	71	Thesis UCRL 20264	Frisch	(LRL)
Also	74	SLAC-PUB-1498 unpub.	Field	(SLAC)
ENSTROM	71	PR D4 2629	+Akavia, Coombes, Dorfan+	(SLAC, STAN)
Also	70	Thesis SLAC-0125	Enstrom	(STAN)
JAMES	71	PL 35B 265	+Montanet, Paul, Pauli+	(CERN, SACL, OSLO)
MEISNER	71	PR D3 59	+Mann, Hertzbach, Kofler+	(MASA, BNL, YALE)
PEACH	71	PL 35B 351	+Evans, Muir, Budagov, Hopkins+	(EDIN, CERN)
REPELLIN	71	PL 36B 603	+Wolff, Chollet, Gaillard, Jane+	(ORSAY, CERN)
WEBBER	71	PR D3 64	+Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	68	PRL 21 498	Webber, Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	69	Thesis UCRL 19226	Webber	(LRL)
WOLFF	71	PL 36B 517	+Chollet, Repellin, Gaillard+	(ORSAY, CERN)
ALBROW	70	PL 33B 516	+Aston, Barber, Bird, Ellison+	(MCHS, DARE)
ARONSON	70	PRL 25 1057	+Ehrlich, Hofer, Jensen+	(EFI, ILLC, SLAC)
BARMIN	70	PL 33B 377	+Barylov, Borisov, Bysheva+	(ITEP, JINR)
BASILE	70	PR D2 78	+Cronin, Thevent, Turlay, Zylberajch+	(SACL)
BECHERRAWY	70	PR D1 1452		(ROCH)
BUCHANAN	70	PL 33B 623	+Drickey, Rudnick, Shepard+	(SLAC, JHU, UCLA)
Also	71	Private Comm.	Cox	
BUDAGOV	70	PR D2 815	+Cundy, Myatt, Nezrick+	(CERN, ORSAY, EPOL)
Also	68B	PL 28B 215	Budagov, Cundy, Myatt+	(CERN, ORSAY, EPOL)
CHIEN	70	PL 33B 627	+Cox, Ettlinger+	(JHU, SLAC, UCLA)
Also	71	Private Comm.	Cox	
CHO	70	PR D1 3031	+Dralle, Canter, Engler, Fisk+	(CMU, BNL, CASE)
Also	67	PRL 19 668	Hill, Luers, Robinson, Sakitt+	(BNL, CMU)
CHOLLET	70	PL 31B 658	+Gaillard, Jane, Ratcliffe, Repellin+	(CERN)
CULLEN	70	PL 32B 523	+Darriulat, Deutsch, Foeth+	(AACH, CERN, TORI)
DARRIULAT	70	PL 33B 249	+Ferrero, Grosso, Holder+	(AACH, CERN, TORI)
FAISSNER	70	NC 70A 57	+Reithler, Thome, Gaillard+	(AACH3, CERN, RHEL)
GINSBERG	70	PR D1 229		(HAIF)
JENSEN	70	Thesis		(EFI)
Also	69	PRL 23 615	Jensen, Aronson, Ehrlich, Fryberger+	(EFI, ILL)
MARX	70	PL 32B 219	+Nygren, Peoples+	(COLU, HARV, CERN)
Also	70B	Thesis Nevis 179	Marx	(COLU)
SCRIBANO	70	PL 32B 224	+Mannelli, Pierazzini, Marx+	(PISA, COLU, HARV)
SMITH	70	PL 32B 133	+Wang, Whatley, Zorn, Hornbostel	(UMD, BNL)
WEBBER	70	PR D1 1967	+Solmitz, Crawford, Alston-Garnjost	(LRL)
Also	69	Thesis UCRL 19226	Webber	(LRL)
BANNER	69	PR 188 2033	+Cronin, Liu, Pilcher	(PRIN)
Also	68	PRL 21 1103	Banner, Cronin, Liu, Pilcher	(PRIN)
Also	68	PRL 21 1107	Cronin, Liu, Pilcher	(PRIN)
BEILLIERE	69	PL 30B 202	+Boutang, Limon	(EPOL)
BENNETT	69	PL 29B 317	+Nygren, Saal, Steinberger+	(COLU, BNL)
BOHM	69B	NP B9 605	+Darriulat, Grosso, Kaftanov+	(CERN)
Also	68	PL 27B 321	Bohm, Darriulat, Grosso, Kaftanov	(CERN)
CENCE	69	PRL 22 1210	+Jones, Peterson, Stenger+	(HAWA, LRL)
EVANS	69	PRL 23 427	+Golden, Muir, Peach+	(EDIN, CERN)
FAISSNER	69	PL 30B 204	+Foeth, Staude, Tittel+	(AACH3, CERN, TORI)
FOETH	69	PL 30B 282	+Holder, Radermacher+	(AACH, CERN, TORI)
GAILLARD	69	NC 59A 453	+Galbraith, Hussri, Jane+	(CERN, RHEL, AACH)
Also	67	PRL 18 20	Gaillard, Krienen, Galbraith+	(CERN, RHEL, AACH)
GOBBI	69B	PRL 22 685	+Green, Hakel, Moffett, Rosen, Goz+	(ROCH, RUTG)
LITTENBERG	69	PRL 22 654	+Field, Piccioni, Mehlhop+	(UCSD)
LONGO	69	PR 181 1808	+Young, Helland	(MICH, UCLA)
PACIOTTI	69	Thesis UCRL 19446		(LRL)
SAAL	69	Thesis		(COLU)
ABRAMS	68B	PR 176 1603	+Abashian, Mischke, Nefkens, Smith+	(ILL)
ARNOLD	68B	PL 28B 56	+Budagov, Cundy, Aubert+	(CERN, ORSAY)
ARONSON	68	PRL 20 287	+Chen	(PRIN)
Also	69	PR 175 1708	Aronson, Chen	(PRIN)
BARTLETT	68	PRL 21 558	+Carnegie, Fitch+	(PRIN)
BASILE	68	PL 26B 542	+Cronin, Thevenet, Turlay+	(SACL)
BASILE	68B	PL 28B 58	+Cronin, Thevenet, Turlay, Zylberajch+	(SACL)
BENNETT	68	PL 27B 244	+Nygren, Steinberger+	(COLU, CERN)
BENNETT	68B	PL 27B 248	+Nygren, Steinberger+	(COLU, CERN)
BLANPIED	68	PRL 21 1650	+Levit, Engels+	(CASE, HARV, MCGI)
BOHM	68B	PL 27B 594	+	
BUDAGOV	68	NC 57A 182	+Burmeister, Cundy+	(CERN, ORSAY, IPNP)
Also	68B	PL 28B 215	Budagov, Cundy, Myatt+	(CERN, ORSAY, EPOL)
JAMES	68	NP B8 365	+Briand	(IPNP, CERN)
Also	68	PRL 21 257	Helland, Longo, Young	(UCLA, MICH)
KULYUKINA	68	JETP 26 20	+Mestvirishvili, Nyagu+	(JINR)
		Translated from ZETF 53 29.		
KUNZ	68	Thesis PU-68-46		(PRIN)
BENNETT	67	PRL 19 993	+Nygren, Saal, Steinberger+	(COLU)
BOTT-...	67	PL 24B 194	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
BOTT-...	67B	PL 24B 438	Bott-Bodenhausen, Debouard, Dekkers+	(CERN)
Also	66B	PL 20 212	Bott-Bodenhausen, Debouard, Cassel+	(CERN)
Also	66	PL 23 277	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
CRONIN	67	PRL 18 25	+Kunz, Risk, Wheeler	(PRIN)
Also	68	Thesis unpub.	Wheeler	(PRIN)
CRONIN	67B	Princeton 11/67	+Kunz, Risk, Wheeler	(PRIN)
DEBOUARD	67	NC 52A 662	+Dekkers, Jordan, Mermod+	(CERN)
Also	65	PL 15 58	DeBouard, Dekkers, Scharff+	(CERN, ORSAY, MPIM)
DEVLIN	67	PRL 18 54	+Solomon, Shepard, Beall+	(PRIN, UMD)
Also	68	PR 169 1045	Sayer, Beall, Devlin, Shephard+	(UMD, PPA, PRIN)
DORFAN	67	PRL 19 987	+Enstrom, Raymond, Schwartz+	(SLAC, LRL)
FELDMAN	67B	PR 155 1611	+Frankel, Highland, Sloan	(PENN)
FIRESTONE	67	PRL 18 176	+Kim, Lach, Sandweiss+	(YALE, BNL)
FITCH	67	PR 164 1711	+Roth, Russ, Vernon	(PRIN)
GINSBERG	67	PR 162 1570		(MASB)
HAWKINS	67	PR 156 1444		(YALE)
HILL	67	PRL 19 668	+Luers, Robinson, Sakitt+	(BNL, CMU)
HOPKINS	67	PRL 19 185	+Bacon, Eisler	(BNL)
KADYK	67	PRL 19 597	+Chan, Drijard, Oren, Sheldon	(LRL)
KULYUKINA	67	Preprint	+Mestvirishvili, Nyagu+	(JINR)
LOWYS	67	PL 24B 75	+Aubert, Chounet, Pascaud+	(EPOL, ORSAY)
MISCHKE	67	PRL 18 138	+Abashian, Abrams+	(ILL)
NEFKENS	67	PR 157 1233	+Abashian, Abrams, Carpenter, Fisher+	(ILL)
SCHMIDT	67	Thesis Nevis 160		(COLU)
TODOROFF	67	Thesis		(ILL)
ALFF-...	66B	PL 21 595	Alff-Steinberger, Heuer, Kleinknecht+	(CERN)
ANIKINA	66	SJNP 2 339	+Vardenga, Zhuravleva+	(JINR)
		Translated from YAF 2 471.		
AUERBACH	66B	PRL 17 980	+Mann, McFarlane, Sciulli	(PENN)
BASILE	66	Balaton Conf.	+Cronin, Thevenet+	(SACL)
BEHR	66	PL 22 540	+Brisson, Petiau+	(EPOL, MILA, PADO, ORSAY)
BOTT-...	66	PL 23 277	Bott-Bodenhausen, DeBouard, Cassel+	(CERN)
CARPENTER	66	PR 142 871	+Abashian, Abrams, Fisher	(ILL)
CRIEGEE	66	PRL 17 150	+Fox, Frauenfelder, Hanson, Moscat+	(ILL)
FIRESTONE	66	PRL 16 556	+Kim, Lach, Sandweiss+	(YALE, BNL)
HAWKINS	66	PL 21 238		(YALE)
Also	67	PR 156 1444	Hawkins	(YALE)
ANDERSON	65	PRL 14 475	+Crawford, Golden, Stern, Binford+	(LRL, WISC)
ANIKINA	65	JINR P 2488	+Vardenga, Zhuravleva, Kotlya+	(JINR)
ASTBURY	65	PL 16 80	+Finocchiaro, Beusch+	(CERN, ZURI)
Also	65	HPA 39 523	Pepin	
ASTBURY	65B	PL 18 175	+Michelini, Beusch+	(CERN, ZURI)
ASTBURY	65C	PL 18 178	+Michelini, Beusch+	(CERN, ZURI)
AUBERT	65	PL 17 59	+Behr, Canavan, Chounet+	(EPOL, ORSAY)
Also	67	PL 24B 75	Lowys, Aubert, Chounet, Pascaud+	(EPOL, ORSAY)
BALDO-...	65	NC 38 684	Baldo-Ceolin, Calimani, Ciampolillo+	(PADO)
FISHER	65	ANL 7130 83	+Abashian, Abrams, Carpenter+	(ILL)
FITCH	65	PRL 15 73	+Roth, Russ, Vernon	(PRIN)
FRANZINI	65	PR 140B 127	+Kirsch, Plano+	(COLU, RUTG)
GALBRAITH	65	PRL 14 383	+Manning, Jones+	(AERE, BRIS, RHEL)
GUIDONI	65	Argonne Conf. 49	+Barnes, Foelsche, Ferbel, Firestone+	(BNL, YALE)
HOPKINS	65	Argonne Conf. 67	+Bacon, Eisler	(VAND, RUTG)
ADAIR	64	PL 12 67	+Leipuner	(YALE, BNL)
ALEKSANYAN	64B	Dubna Conf. 2 102	+Alikhanyan, Vartazaryan+	(YERE)
Also	64	JETP 19 1019	Aleksanyan+	(LEBD, MPEI, YERE)
		Translated from ZETF 46 1504.		
ANIKINA	64	JETP 19 42	+Zhuravleva+	(GEOR, JINR)
		Translated from ZETF 46 59.		
CHRISTENS...	64	PRL 13 138	Christenson, Cronin, Fitch, Turlay	(PRIN)
FUJII	64	Dubna Conf. 2 146	+Jovanovich, Turkot+	(BNL, UMD, MIT)
LUERS	64	PR 133B 1276	+Mittra, Willis, Yamamoto	(BNL)
DARMON	62	PL 3 57	+Rousset, Six	(EPOL)
ASTIER	61	Aix Conf. 1 227	+Blaskovic, Rivet, Siaud+	(EPOL)
FITCH	61	NC 22 1160	+Piroue, Perkins	(PRIN, LASL)
GOOD	61	PR 124 1223	+Matsen, Muller, Piccioni+	(LRL)
NYAGU	61	PRL 6 552	+Okonov, Petrov, Rosanova, Rusakov	(JINR)
Also	61B	JETP 13 1138	Nyagu, Okonov, Petrov, Rozanova+	(JINR)
		Translated from ZETF 40 1618.		
BARDON	58	ANP 5 156	+Lande, Lederman	(COLU, BNL)

OTHER RELATED PAPERS

HAYAKAWA	93	PR D48 1150	+Sanda	(NAGO)
"Searching for *T*, *CP*, *CPT*, $\Delta S = \Delta Q$ Rule Violations in the Neutral *K* Meson System: A Guide"				
LITTENBERG	93	ARNPS 43 729	+Valencia	(BNL, FNAL)
Rare and Radiative Kaon Decays				
RITCHIE	93	RMP 65 1149	+Wojcicki	
"Rare *K* Decays"				
WINSTEIN	93	RMP 65 1113	+Wolfenstein	
"The Search for Direct *CP* Violation"				
BATTISTON	92	PRPL 214 293	+Cocolicchio, Fogli, Paver	(PGIA, CERN, TRSTT)
Status and Perspectives of *K* Decay Physics				
DIB	92	PR D46 2265	+Peccei	(UCLA)
Tests of *CPT* conservation in the neutral kaon system.				
KLEINKNECHT	92	CNPP 20 281		(MANZ)
New Results on *CP* Violation in Decays of Neutral *K* Mesons.				
KLEINKNECHT	90	ZPHY C46 S57		(MANZ)
PEACH	90	JPG 16 131		(EDIN)
BRYMAN	89	IJMP A4 79		(TRIU)
"Rare Kaon Decays"				
KLEINKNECHT	76	ARNS 26 1		(DORT)

GINSBERG 73 PR D8 3887 +Smith (MIT, STON)
GINSBERG 70 PR D1 229 (HAIF)
HEUSSE 70 LNC 3 449 +Aubert, Pascaud, Vialle (ORSAY)
CRONIN 68C Vienna Conf. 281 (PRIN)
RUBBIA 67 PL 24B 531 +Steinberger (CERN, COLU)
Also 66C PL 23 167 Rubbia, Steinberger (CERN, COLU)
Also 66C PL 20 207 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
Also 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
AUERBACH 66 PR 149 1052 +Dobbs, Lande, Mann, Sciulli+ (PENN)
Also 65 PRL 14 192 Auerbach, Lande, Mann, Sciulli, Uto+ (PENN)
FIRESTONE 66B PRL 17 116 +Kim, Lach, Sandweiss+ (YALE, BNL)
BEHR 65 Argonne Conf. 59 +Brisson, Bellotti+ (EPOL, MILA, PADO)
MESTVIRISH... 65 JINR P 2449 Mestvirishvili, Nyagu, Petrov, Rusakov+ (JINR)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
JOVANOV... 63 BNL Conf. 42 Jovanovich, Fischer, Burris+ (BNL, UMD)

$\boxed{K^*(892)}$

$I(J^P) = \frac{1}{2}(1^-)$

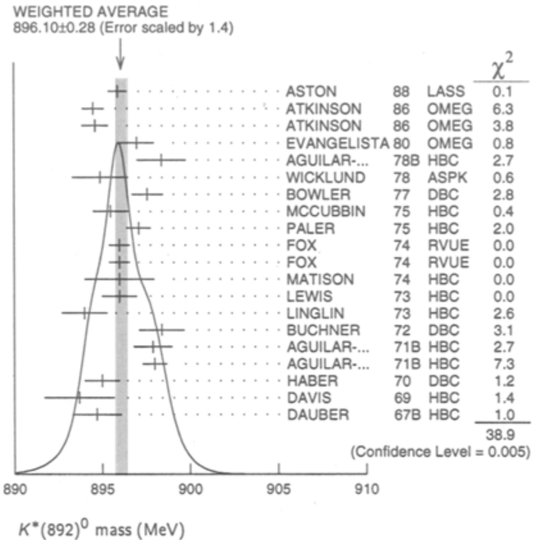
$K^*(892)$ MASS

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
891.66±0.26 OUR AVERAGE						
892.6 ±0.5	5840	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
888 ±3		NAPIER	84	SPEC	+	200 $\pi^- p \to 2K^0_S X$
891 ±1		NAPIER	84	SPEC	−	200 $\pi^- p \to 2K^0_S X$
891.7 ±2.1	3700	BARTH	83	HBC	+	70 $K^+ p \to K^0 \pi^+ X$
891 ±1	4100	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
892.8 ±1.6		AJINENKO	80	HBC	+	32 $K^+ p \to K^0 \pi^+ X$
890.7 ±0.9	1800	AGUILAR-...	78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
886.6 ±2.4	1225	BALAND	78	HBC	±	12 $\overline{p} p \to (K\pi)^\pm X$
891.7 ±0.6	6706	COOPER	78	HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
891.9 ±0.7	9000	[1] PALER	75	HBC	−	14.3 $K^- p \to (K\pi)^- X$
892.2 ±1.5	4404	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
891 ±2	1000	CRENNELL	69D	DBC	−	3.9 $K^- N \to K^0 \pi^- X$
890 ±3.0	720	BARLOW	67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K^\mp$
889 ±3.0	600	BARLOW	67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K \pi$
891 ±2.3	620	[2] DEBAERE	67B	HBC	+	3.5 $K^+ p \to K^0 \pi^+ p$
891.0 ±1.2	1700	[3] WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
890.4 ±0.2 ±0.5	79709±801	[4] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
890.0 ±2.3	800	[2,3] CLELAND	82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
896.0 ±1.1	3200	[2,3] CLELAND	82	SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
893 ±1	3600	[2,3] CLELAND	82	SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
896.0 ±1.9	380	DELFOSSE	81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
886.0 ±2.3	187	DELFOSSE	81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$
894.2 ±2.0	765	[2] CLARK	73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
894.3 ±1.5	1150	[2,3] CLARK	73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
892.0 ±2.6	341	[2] SCHWEING...	68	HBC	−	5.5 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
896.10±0.28 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.					
895.9 ±0.5 ±0.2		ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
894.52±0.63	25k	[1] ATKINSON	86	OMEG		20–70 γp
894.63±0.76	20k	[1] ATKINSON	86	OMEG		20–70 γp
897 ±1	28k	EVANGELISTA	80	OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda, \Sigma)$
898.4 ±1.4	1180	AGUILAR-...	78B	HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
894.9 ±1.6		WICKLUND	78	ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
897.6 ±0.9		BOWLER	77	DBC	0	5.4 $K^+ d \to K^+ \pi^- p p$
895.5 ±1.0	3600	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
897.1 ±0.7	22k	[1] PALER	75	HBC	0	14.3 $K^- p \to (K\pi)^0 X$
896.0 ±0.6	10k	FOX	74	RVUE	0	2 $K^- p \to K^- \pi^+ n$
896.0 ±0.6		FOX	74	RVUE	0	2 $K^+ n \to K^+ \pi^- p$
896 ±2		[5] MATISON	74	HBC	0	12 $K^+ p \to K^+ \pi^- \Delta$
896 ±1	3186	LEWIS	73	HBC	0	2.1–2.7 $K^+ p \to K \pi \pi p$
894.0 ±1.3		[5] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- \pi^+ p$
898.4 ±1.3	1700	[2] BUCHNER	72	DBC	0	4.6 $K^+ n \to K^+ \pi^- p$
897.9 ±1.1	2934	[2] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ n$
898.0 ±0.7	5362	[2] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ \pi^- p$
895 ±1	4300	[3] HABER	70	DBC	0	3 $K^- N \to K^- \pi^+ X$
893.7 ±2.0	10k	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$
894.7 ±1.4	1040	[2] DAUBER	67B	HBC	0	2.0 $K^- p \to K^- \pi^+ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
900.7 ±1.1	5900	BARTH	83	HBC	0	70 $K^+ p \to K^+ \pi^- X$



[1] Inclusive reaction. Complicated background and phase-space effects.
[2] Mass errors enlarged by us to $\Gamma/\sqrt{N}$. See note.
[3] Number of events in peak reevaluated by us.
[4] From a partial wave amplitude analysis.
[5] From pole extrapolation.

$K^*(892)$ MASSES AND MASS DIFFERENCES

Unrealistically small errors have been reported by some experiments. We use simple "realistic" tests for the minimum errors on the determination of a mass and width from a sample of N events:

$$\delta_{\min}(m) = \frac{\Gamma}{\sqrt{N}}, \quad \delta_{\min}(\Gamma) = 4\frac{\Gamma}{\sqrt{N}}\ .$$

We consistently increase unrealistic errors before averaging. For a detailed discussion, see the 1971 edition of this Note.

$m_{K^*(892)^0} - m_{K^*(892)^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
6.7±1.2 OUR AVERAGE						
7.7±1.7	2980	AGUILAR-...	78B	HBC	±0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
5.7±1.7	7338	AGUILAR-...	71B	HBC	−0	3.9,4.6 $K^- p$
6.3±4.1	283	[6] BARASH	67B	HBC		0.0 $\overline{p} p$

[6] Number of events in peak reevaluated by us.

$K^*(892)$ RANGE PARAMETER

All from partial wave amplitude analyses.

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
3.4±0.7	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.1±3.2±3.0	BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$

$K^*(892)$ WIDTH

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
50.8±0.9 OUR FIT						
50.8±0.9 OUR AVERAGE						
49 ±2	5840	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
56 ±4		NAPIER	84	SPEC	−	200 $\pi^- p \to 2K^0_S X$
51 ±2	4100	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
50.5±5.6		AJINENKO	80	HBC	+	32 $K^+ p \to K^0 \pi^+ X$
45.8±3.6	1800	AGUILAR-...	78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
52.0±2.5	6706	[7] COOPER	78	HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
52.1±2.2	9000	[8] PALER	75	HBC	−	14.3 $K^- p \to (K\pi)^- X$
46.3±6.7	765	[7] CLARK	73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
48.2±5.7	1150	[7,9] CLARK	73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
54.3±3.3	4404	[7] AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
46 ±5	1700	[7,9] WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
45.2±1 ±2	79709±801	[10] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
42.8±7.1	3700	BARTH	83	HBC	+	70 $K^+ p \to K^0 \pi^+ X$
64.0±9.2	800	[7,9] CLELAND	82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
62.0±4.4	3200	[7,9] CLELAND	82	SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
55 ±4	3600	[7,9] CLELAND	82	SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
62.6±3.8	380	DELFOSSE	81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
50.5±3.9	187	DELFOSSE	81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
50.5±0.6 OUR FIT Error includes scale factor of 1.1.						
50.5±0.6 OUR AVERAGE Error includes scale factor of 1.1.						
50.8±0.8±0.9		ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
46.5±4.3	5900	BARTH	83	HBC	0	70 $K^+ p \to K^+ \pi^- X$
54 ±2	28k	EVANGELISTA	80	OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda, \Sigma)$
45.9±4.8	1180	AGUILAR-...	78B	HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
51.2±1.7		WICKLUND	78	ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
48.9±2.5		BOWLER	77	DBC	0	5.4 $K^+ d \to K^+ \pi^- p p$
48 $^{+3}_{-2}$	3600	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
50.6±2.5	22k	[8] PALER	75	HBC	0	14.3 $K^- p \to (K\pi)^0 X$
47 ±2	10k	FOX	74	RVUE	0	2 $K^- p \to K^- \pi^+ n$
51 ±2		FOX	74	RVUE	0	2 $K^+ n \to K^+ \pi^- p$
46.0±3.3	3186	[7] LEWIS	73	HBC	0	2.1–2.7 $K^+ p \to K \pi \pi p$
51.4±5.0	1700	[7] BUCHNER	72	DBC	0	4.6 $K^+ n \to K^+ \pi^- p$
55.8$^{+4.2}_{-3.4}$	2934	[7] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ n$
48.5±2.7	5362	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ \pi^- p$
54.0±3.3	4300	[7,9] HABER	70	DBC	0	3 $K^- N \to K^- \pi^+ X$
53.2±2.1	10k	[7] DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$
44 ±5.5	1040	[7] DAUBER	67B	HBC	0	2.0 $K^- p \to K^- \pi^+ \pi^- p$

[7] Width errors enlarged by us to 4 × $\Gamma/\sqrt{N}$; see note.
[8] Inclusive reaction. Complicated background and phase-space effects.
[9] Number of events in peak reevaluated by us.
[10] From a partial wave amplitude analysis.

$K^*(892)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\pi$	∼ 100 %	
Γ_2	$(K\pi)^\pm$	(99.901±0.009) %	
Γ_3	$(K\pi)^0$	(99.770±0.020) %	
Γ_4	$K^0\gamma$	(2.30 ±0.20) × 10^{-3}	
Γ_5	$K^\pm\gamma$	(9.9 ±0.9) × 10^{-4}	
Γ_6	$K\pi\pi$	< 7 × 10^{-4}	95%

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 13 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 7.8$ for 11 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_5 & -100 & \\ \Gamma & 19 & -19 \\ \hline & x_2 & x_5 \end{array}$$

	Mode	Rate (MeV)
Γ_2	$(K\pi)^\pm$	50.7 ±0.9
Γ_5	$K^\pm\gamma$	0.050±0.005

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 18.4$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_4 & -100 & \\ \Gamma & 14 & -14 \\ \hline & x_3 & x_4 \end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_3	$(K\pi)^0$	50.4 ±0.6	1.1
Γ_4	$K^0\gamma$	0.117±0.010	

$K^*(892)$ PARTIAL WIDTHS

$\Gamma(K^0\gamma)$ Γ_4

VALUE (keV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
116 ±10 OUR FIT						
116.5± 9.9	584	CARLSMITH	86	SPEC	0	$K^0_L A \to K^0_S \pi^0 A$

$\Gamma(K^\pm\gamma)$ Γ_5

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
50± 5 OUR FIT					
50± 5 OUR AVERAGE					
48±11	BERG	83	SPEC	−	156 $K^- A \to \overline{K} \pi A$
51± 5	CHANDLEE	83	SPEC	+	200 $K^+ A \to K \pi A$

$K^*(892)$ BRANCHING RATIOS

$\Gamma(K^0\gamma)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	CHG	COMMENT
2.30±0.20 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.7	CARITHERS	75B	CNTR	0	8–16 $\overline{K}^0 A$

$\Gamma(K^\pm\gamma)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
0.99±0.09 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.6	95	BEMPORAD	73	CNTR	+	10–16 $K^+ A$

$\Gamma(K\pi\pi)/\Gamma((K\pi)^\pm)$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.0007	95	JONGEJANS	78	HBC		4 $K^- p \to p \overline{K}^0 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.002		WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$

$K^*(892)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CARLSMITH	86	PRL 56 18	+Bernstein, Peyaud, Turlay	(EFI, SACL)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
NAPIER	84	PL 149B 514	+Chen+	(TUFTS, ARIZ, FNAL, FLOR, NDAM+)
BARTH	83	NP B223 296	+Drevermann+	(BRUX, CERN, GENO, MONS+)
BERG	83	Thesis UMI 83-21652		(ROCH)
CHANDLEE	83	PRL 51 168	+Berg, Cihangir, Collick+	(ROCH, FNAL, MINN)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
AJINENKO	80	ZPHY C5 177	+Barth, Dujardin+	(SERP, BRUX, MONS, SACL)
EVANGELISTA	80	NP B165 383	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
AGUILAR-...	78B	NP B141 101	Aguilar-Benitez+	(MADR, TATA, CERN+)
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)
COOPER	78	NP B136 365	+Gurtu+	(TATA, CERN, CDEF+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
CARITHERS	75B	PRL 35 349	+Muhlemann, Underwood+	(ROCH, MCGI)
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
PALER	75	NP B96 1	+Tovey, Shah, Spiro+	(RHEL, SACL, EPOL)
FOX	74	NP B80 403	+Griss	(CIT)
MATISON	74	PR D9 1872	+Galtieri, Alston-Garnjost, Flatte, Friedman+	(LBL)
BEMPORAD	73	NP B51 1	+Beusch, Freudenreich+	(CERN, ETH, LOIC)
CLARK	73	NP B54 432	+Lyons, Radojicic	(OXF)
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
LINGLIN	73	NP B55 408		(CERN)
BUCHNER	72	NP B45 333	+Dehm, Charriere, Cornet+	(MPIM, CERN, BRUX)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
HABER	70	NP B17 289	+Shapira, Alexander+	(REHO, SACL, BGNA, EPOL)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
DAUBER	67B	PR 153 1403	+Schlein, Slater, Ticho	(UCLA)
DEBAERE	67B	NC 51A 401	+Goldschmidt-Clermont, Henri+	(BRUX, CERN)
WOJCICKI	64	PR 135B 484		(LRL)

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
NAPIER	84	PL 149B 514	+Chen+	(TUFTS, ARIZ, FNAL, FLOR, NDAM+)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ALEXANDER	62	PRL 8 447	+Kalbfleisch, Miller, Smith	(LRL)
ALSTON	61	PRL 6 300	+Alvarez, Eberhard, Good+	(LRL)

$K_1(1270)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1270)$ MASS

VALUE (MeV)	DOCUMENT ID
1273±7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1275±10	700	GAVILLET 78	HBC	+	4.2 $K^- p \to \Xi^- (K\pi\pi)^+$

PRODUCED BY K BEAMS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1270±10	DAUM 81C	CNTR	−	63 $K^- p \to K^- 2\pi p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 1276	[1] TORNQVIST 82B	RVUE		
~ 1300	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
1289±25	[2] CARNEGIE 77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 1300	BRANDENB... 76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 1270	OTTER 76	HBC	−	10,14,16 $K^- p \to (\overline{K}\pi\pi)^- p$
1260	DAVIS 72	HBC	+	12 $K^+ p$
1234±12	FIRESTONE 72B	DBC	+	12 $K^+ d$

[1] From a unitarized quark-model calculation.

[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

PRODUCED BY BEAMS OTHER THAN K MESONS

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1294±10	310	RODEBACK 81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
1300	40	CRENNELL 72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
1242^{+9}_{-10}		[3] ASTIER 69	HBC	0	$\overline{p}p$
1300	45	CRENNELL 67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

[3] This was called the C meson.

$K_1(1270)$ WIDTH

VALUE (MeV)	DOCUMENT ID
90±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
87± 7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
75±15	700	GAVILLET 78	HBC	+	4.2 $K^- p \to \Xi^- K\pi\pi$

PRODUCED BY K BEAMS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
90± 8	DAUM 81C	CNTR	−	63 $K^- p \to K^- 2\pi p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 150	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
150±71	[4] CARNEGIE 77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
~ 200	BRANDENB... 76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
120	DAVIS 72	HBC	+	12 $K^+ p$
188±21	FIRESTONE 72B	DBC	+	12 $K^+ d$

[4] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

PRODUCED BY BEAMS OTHER THAN K MESONS

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
66±15	310	RODEBACK 81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
60	40	CRENNELL 72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
127^{+7}_{-25}		ASTIER 69	HBC	0	$\overline{p}p$
60	45	CRENNELL 67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

$K_1(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\rho$	(42 ±6) %
Γ_2	$K_0^*(1430)\pi$	(28 ±4) %
Γ_3	$K^*(892)\pi$	(16 ±5) %
Γ_4	$K\omega$	(11.0±2.0) %
Γ_5	$K f_0(1370)$	(3.0±2.0) %

$K_1(1270)$ PARTIAL WIDTHS

$\Gamma(K\rho)$ — Γ_1

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
57±5	MAZZUCATO 79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
75±6	CARNEGIE 77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K_0^*(1430)\pi)$ — Γ_2

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
26±6	CARNEGIE 77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K^*(892)\pi)$ — Γ_3

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
14±11	MAZZUCATO 79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
2± 2	CARNEGIE 77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ — Γ_4

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
4±4	MAZZUCATO 79	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$
24±3	CARNEGIE 77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K f_0(1370))$ — Γ_5

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
22±5	CARNEGIE 77B	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$K_1(1270)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.42±0.06	[5] DAUM 81C	CNTR	63 $K^- p \to K^- 2\pi p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	RODEBACK 81	HBC	4 $\pi^- p \to \Lambda K 2\pi$

$\Gamma(K_0^*(1430)\pi)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.28±0.04	[5] DAUM 81C	CNTR	63 $K^- p \to K^- 2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.05	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\omega)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.11 ±0.02	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\omega)/\Gamma(K\rho)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	95	RODEBACK	81	HBC	4 $\pi^- p \rightarrow \Lambda K 2\pi$

$\Gamma(K f_0(1370))/\Gamma_{\rm total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.02	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1270) \rightarrow K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
1.0±0.7	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

[5] Average from low and high t data.

$K_1(1270)$ REFERENCES

TORNQVIST 82B NP B203 268 (HELS)
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
RODEBACK 81 ZPHY C9 9 +Sjogren+ (CERN, CDEF, MADR, STOH)
MAZZUCATO 79 NP B156 532 +Pennington+ (CERN, ZEEM, NIJM, OXF)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)
GAVILLET 78 PL 76B 517 +Diaz, Dionisi+ (AMST, CERN, NIJM, OXF) JP
CARNEGIE 77 NP B127 509 +Cashmore, Davier, Dunwoodie, Lasinski+ (SLAC)
CARNEGIE 77B PL 68B 287 +Cashmore, Dunwoodie, Lasinski+ (SLAC)
BRANDENB... 76 PRL 26 703 Brandenburg, Carnegie, Cashmore+ (SLAC) JP
OTTER 76 NP B106 77 + (AACH3, BERL, CERN, LOIC, VIEN, EPOL+) JP
CRENNELL 72 PR D6 1220 +Gordon, Lai, Scarr (BNL)
DAVIS 72 PR D5 2688 +Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+ (LBL)
FIRESTONE 72B PR D5 505 +Goldhaber, Lissauer, Trilling (LBL)
ASTIER 69 NP B10 65 +Marechal, Montanet+ (CDEF, CERN, IPNP, LIVP) IJP
CRENNELL 67 PRL 19 44 +Kalbfleisch, Lai, Scarr, Schumann (BNL) I

OTHER RELATED PAPERS

SUZUKI 93 PR D47 1252 (LBL)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, CURIN)
FERNANDEZ 82 ZPHY C16 95 +Aguilar-Benitez+ (MADR, CERN, CDEF, STOH) JP
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)
SHEN 66 PRL 17 726 +Butterworth, Fu, Goldhaber, Trilling (LRL)
  Also 66 Private Comm. Goldhaber (LRL)
ALMEIDA 65 PL 16 184 +Atherton, Byer, Dornan, Forson+ (CAVE)
ARMENTEROS 64 PL 9 207 +Edwards, D'Andlau+ (CERN, CDEF)
  Also 66 PR 145 1095 Barash, Kirsch, Miller, Tan (COLU)

$K_1(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1400)$ MASS

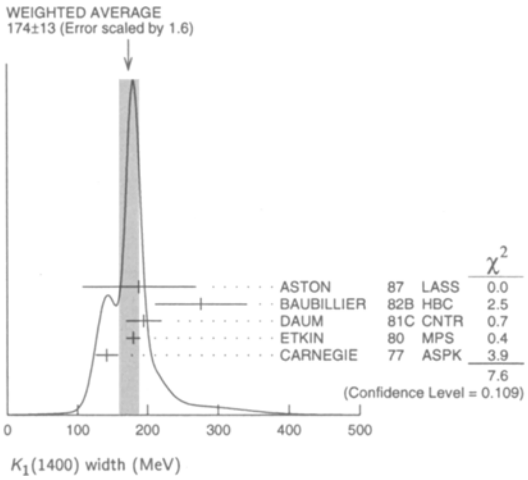
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1402± 7 OUR AVERAGE					
1373±14±18	[1] ASTON	87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
1392±18	BAUBILLIER	82B	HBC	0	8.25 $K^- p \rightarrow K^0_S \pi^+ \pi^- n$
1410±25	DAUM	81C	CNTR	−	63 $K^- p \rightarrow K^- 2\pi p$
1415±15	ETKIN	80	MPS	0	6 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
1404±10	[2] CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1350	[3] TORNQVIST	82B	RVUE		
~ 1400	VERGEEST	79	HBC	−	4.2 $K^- p \rightarrow (\overline{K}\pi\pi)^- p$
~ 1400	BRANDENB...	76	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
1420	DAVIS	72	HBC	+	12 $K^+ p$
1368±18	FIRESTONE	72B	DBC	+	12 $K^+ d$

[1] From partial-wave analysis of $K^0\pi^+\pi^-$ system.
[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.
[3] From a unitarized quark-model calculation.

$K_1(1400)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
174±13 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
188±54±60	[4] ASTON	87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
276±65	BAUBILLIER	82B	HBC	0	8.25 $K^- p \rightarrow K^0_S \pi^+ \pi^- n$
195±25	DAUM	81C	CNTR	−	63 $K^- p \rightarrow K^- 2\pi p$
180±10	ETKIN	80	MPS	0	6 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
142±16	[5] CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 200	VERGEEST	79	HBC	−	4.2 $K^- p \rightarrow (\overline{K}\pi\pi)^- p$
~ 160	BRANDENB...	76	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
80	DAVIS	72	HBC	+	12 $K^+ p$
241±30	FIRESTONE	72B	DBC	+	12 $K^+ d$

[4] From partial-wave analysis of $K^0\pi^+\pi^-$ system.
[5] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.



$K_1(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	(94 ±6) %
Γ_2	$K\rho$	(3.0±3.0) %
Γ_3	$K f_0(1370)$	(2.0±2.0) %
Γ_4	$K\omega$	(1.0±1.0) %
Γ_5	$K^*_0(1430)\pi$	not seen

$K_1(1400)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
117±10	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2 ±1	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
23±12	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$K_1(1400)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.94±0.06	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\rho)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.03	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K f_0(1370))/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ±0.02	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\omega)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.01 ±0.01	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K^*_0(1430)\pi)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1400) \rightarrow K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ±0.01	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

[6] Average from low and high t data.

$K_1(1400)$ REFERENCES

ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
TORNQVIST	82B	NP B203 268		(HELS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC) JP
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)

OTHER RELATED PAPERS

SUZUKI	93	PR D47 1252		(LBL)
FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1410)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1414±15 OUR AVERAGE Error includes scale factor of 1.3.				
1380±21±19	ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$
1420± 7±10	ASTON 87	LASS	0	$11\ K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1367±54	BIRD 89	LASS	–	$11\ K^- p \rightarrow \overline{K}^0 \pi^- p$
1474±25	BAUBILLIER 82B	HBC	0	$8.25\ K^- p \rightarrow \overline{K}^0 2\pi n$
1500±30	ETKIN 80	MPS	0	$6\ K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$

$K^*(1410)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
232± 21 OUR AVERAGE Error includes scale factor of 1.1.				
176± 52±22	ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$
240± 18±12	ASTON 87	LASS	0	$11\ K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114±101	BIRD 89	LASS	–	$11\ K^- p \rightarrow \overline{K}^0 \pi^- p$
275± 65	BAUBILLIER 82B	HBC	0	$8.25\ K^- p \rightarrow \overline{K}^0 2\pi n$
500±100	ETKIN 80	MPS	0	$6\ K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$

$K^*(1410)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K^*(892)\pi$	> 40 %	95%
Γ_2	$K\pi$	(6.6±1.3) %	
Γ_3	$K\rho$	< 7 %	95%

$K^*(1410)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.17	95	ASTON 84	LASS	0	$11\ K^- p \rightarrow \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.16	95	ASTON 84	LASS	0	$11\ K^- p \rightarrow \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.066±0.010±0.008	ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$

$K^*(1410)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP

$K_0^*(1430)$

$I(J^P) = \frac{1}{2}(0^+)$

See our minireview in the 1994 edition and in this edition under the $f_0(1370)$.

$K_0^*(1430)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1429 ± 4±6	[1] ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1415 ±25	[2] ANISOVICH 97C	RVUE		$11\ K^- p \rightarrow K^- \pi^+ n$
~ 1450	[3] TORNQVIST 96	RVUE		$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi$
~ 1430	BAUBILLIER 84B	HBC	–	$8.25\ K^- p \rightarrow \overline{K}^0 \pi^- p$
~ 1425	[4,5] ESTABROOKS 78	ASPK		$13\ K^{\pm} p \rightarrow K^{\pm} \pi^{\pm} (n, \Delta)$
~ 1450.0	MARTIN 78	SPEC		$10\ K^{\pm} p \rightarrow K_S^0 \pi p$

[1] Uses a model for the background, without this background they get a mass 1340 MeV, where the phase shift passes 90°.

[2] T-matrix pole. Reanalysis of ASTON 88 data.

[3] T-matrix pole.

[4] Mass defined by pole position.

[5] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
287±10±21	ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
330±50	[6] ANISOVICH 97C	RVUE		$11\ K^- p \rightarrow K^- \pi^+ n$
~ 320	[7] TORNQVIST 96	RVUE		$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi$
~ 200	BAUBILLIER 84B	HBC	–	$8.25\ K^- p \rightarrow \overline{K}^0 \pi^- p$
200 to 300	[8] ESTABROOKS 78	ASPK		$13\ K^{\pm} p \rightarrow K^{\pm} \pi^{\pm} (n, \Delta)$

[6] T-matrix pole. Reanalysis of ASTON 88 data.

[7] T-matrix pole.

[8] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(93±10) %

$K_0^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.93±0.04±0.09	ASTON 88	LASS	0	$11\ K^- p \rightarrow K^- \pi^+ n$

$K_0^*(1430)$ REFERENCES

ANISOVICH	97C	PL B413 137		
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)

OTHER RELATED PAPERS

TORNQVIST	82	PRL 49 624		(HELS)
GOLDBERG	69	PL 30B 434	+Huffer, Laloum+	(SABRE Collab.)
TRIPPE	68	PL 28B 203	+Chien, Malamud, Mellema, Schlein+	(UCLA)

$K_2^*(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

We consider that phase-shift analyses provide more reliable determinations of the mass and width.

$K_2^*(1430)$ MASS

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1425.6± 1.5 OUR AVERAGE	Error includes scale factor of 1.1.				
1420 ± 4	1587	BAUBILLIER	84B HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
1436 ± 5.5	400	[1,2] CLELAND	82 SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1500	[1,2] CLELAND	82 SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1200	[1,2] CLELAND	82 SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
1423 ± 5	935	TOAFF	81 HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
1428.0± 4.6		[3] MARTIN	78 SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
1423.8± 4.6		[3] MARTIN	78 SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
1420.0± 3.1	1400	AGUILAR-...	71B HBC	−	3.9,4.6 $K^- p$
1425 ± 8.0	225	[1,2] BARNHAM	71C HBC	+	$K^+ p \to K^0 \pi^+ p$
1416 ±10	220	CRENNELL	69D DBC	−	3.9 $K^- N \to \overline{K}^0 \pi^- N$
1414 ±13.0	60	[1] LIND	69 HBC	+	9 $K^+ p \to K^0 \pi^+ p$
1427 ±12	63	[1] SCHWEING...	68 HBC	−	5.5 $K^- p \to \overline{K} \pi N$
1423 ±11.0	39	[1] BASSANO	67 HBC	−	4.6–5.0 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1423.4± 2 ±3	24809± 820	[4] BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1432.4± 1.3 OUR AVERAGE					
1431.2± 1.8± 0.7		[5] ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 4 ± 6		[5] ASTON	87 LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1433 ± 6 ±10		[5] ASTON	84B LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
1471 ±12		[5] BAUBILLIER	82B HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
1428 ± 3		[5] ASTON	81C LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 2		[5] ESTABROOKS	78 ASPK	0	13 $K^\pm p \to p K \pi$
1440 ±10		[5] BOWLER	77 DBC	0	5.5 $K^+ d \to K \pi p p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1420 ± 7	300	HENDRICK	76 DBC		8.25 $K^+ N \to K^+ \pi N$
1421.6± 4.2	800	MCCUBBIN	75 HBC	0	3.6 $K^- p \to K^- \pi^+ n$
1420.1± 4.3		[6] LINGLIN	73 HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
1419.1± 3.7	1800	AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p$
1416 ± 6	600	CORDS	71 DBC	0	9 $K^+ n \to K^+ \pi^- p$
1421.1± 2.6	2200	DAVIS	69 HBC	0	12 $K^+ p \to K^+ \pi^- X$

[1] Errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] Number of events in peak re-evaluated by us.
[3] Systematic error added by us.
[4] From a partial wave amplitude analysis.
[5] From phase shift or partial-wave analysis.
[6] From pole extrapolation, using world $K^+ p$ data summary tape.

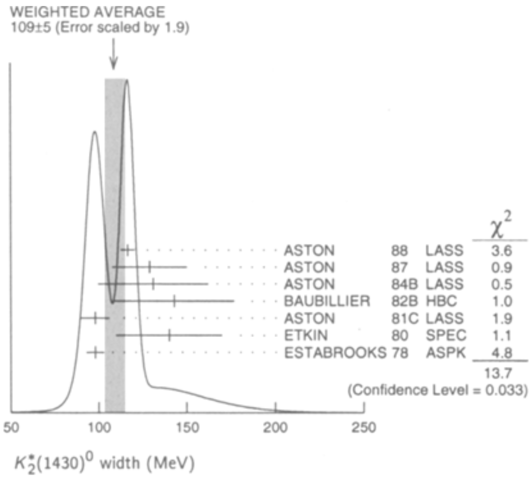
$K_2^*(1430)$ WIDTH

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
98.5± 2.7 OUR FIT	Error includes scale factor of 1.1.				
98.5± 2.9 OUR AVERAGE	Error includes scale factor of 1.1.				
109 ±22	400	[7,8] CLELAND	82 SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
124 ±12.8	1500	[7,8] CLELAND	82 SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
113 ±12.8	1200	[7,8] CLELAND	82 SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
85 ±16	935	TOAFF	81 HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
96.5± 3.8		MARTIN	78 SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
97.7± 4.0		MARTIN	78 SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
$94.7^{+15.1}_{-12.5}$	1400	AGUILAR-...	71B HBC	−	3.9,4.6 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
98 ± 4 ±4	24809± 820	[9] BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
109 ± 5 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.				
116.5± 3.6± 1.7		[10] ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$
129 ±15 ±15		[10] ASTON	87 LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
131 ±24 ±20		[10] ASTON	84B LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
143 ±34		[10] BAUBILLIER	82B HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
98 ± 8		[10] ASTON	81C LASS	0	11 $K^- p \to K^- \pi^+ n$
140 ±30		[10] ETKIN	80 SPEC	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
98 ± 5		[10] ESTABROOKS	78 ASPK	0	13 $K^\pm p \to p K \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
125 ±29	300	[7] HENDRICK	76 DBC		8.25 $K^+ N \to K^+ \pi N$
116 ±18	800	MCCUBBIN	75 HBC	0	3.6 $K^- p \to K^- \pi^+ n$
61 ±14		[11] LINGLIN	73 HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
$116.6^{+10.3}_{-15.5}$	1800	AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p$
144 ±24.0	600	[7] CORDS	71 DBC	0	9 $K^+ n \to K^+ \pi^- p$
101 ±10	2200	DAVIS	69 HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$



[7] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[8] Number of events in peak re-evaluated by us.
[9] From a partial wave amplitude analysis.
[10] From phase shift or partial-wave analysis.
[11] From pole extrapolation, using world $K^+ p$ data summary tape.

$K_2^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\pi$	(49.9±1.2) %	
Γ_2	$K^*(892)\pi$	(24.7±1.5) %	
Γ_3	$K^*(892)\pi\pi$	(13.4±2.2) %	
Γ_4	$K\rho$	(8.7±0.8) %	S=1.2
Γ_5	$K\omega$	(2.9±0.8) %	
Γ_6	$K^+\gamma$	(2.4±0.5) × 10^{-3}	S=1.1
Γ_7	$K\eta$	($1.5^{+3.4}_{-1.0}$) × 10^{-3}	S=1.3
Γ_8	$K\omega\pi$	< 7.2 × 10^{-4}	CL=95%
Γ_9	$K^0\gamma$	< 9 × 10^{-4}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 10 branching ratios uses 31 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 20.2$ for 24 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccccccc}
x_2 & -9 \\
x_3 & -40 & -73 \\
x_4 & -8 & 36 & -52 \\
x_5 & -11 & -3 & -26 & -7 \\
x_6 & -1 & -1 & -1 & -1 & 0 \\
x_7 & -4 & -7 & -5 & -5 & -2 & 0 \\
\Gamma & 0 & 0 & 0 & 0 & 0 & -13 & 0 \\
\hline
 & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7
\end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_1	$K\pi$	49.1 ± 1.8	
Γ_2	$K^*(892)\pi$	24.3 ± 1.6	
Γ_3	$K^*(892)\pi\pi$	13.2 ± 2.2	
Γ_4	$K\rho$	8.5 ± 0.8	1.2
Γ_5	$K\omega$	2.9 ± 0.8	
Γ_6	$K^+\gamma$	0.24 ± 0.05	1.1
Γ_7	$K\eta$	$0.15^{+0.33}_{-0.10}$	1.3

$K_2^*(1430)$ PARTIAL WIDTHS

$\Gamma(K^+\gamma)$ Γ_6

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
241±50 OUR FIT	Error includes scale factor of 1.1.			
240±45	CIHANGIR 82	SPEC	+	$200\ K^+ Z \to Z K^+ \pi^0$, $Z K_S^0 \pi^+$

$\Gamma(K^0\gamma)$ Γ_9

VALUE (keV)	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<84	90	CARLSMITH 87	SPEC	0	$60\text{–}200\ K_L^0 A \to K_S^0 \pi^0 A$

$K_2^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.499±0.012 OUR FIT				
0.488±0.014 OUR AVERAGE				
0.485±0.006±0.020	[12] ASTON 88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
0.49 ±0.02	[12] ESTABROOKS 78	ASPK	±	$13\ K^\pm p \to p K \pi$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.496±0.034 OUR FIT				
0.47 ±0.04 OUR AVERAGE				
0.44 ±0.09	ASTON 84B	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$
0.62 ±0.19	LAUSCHER 75	HBC	0	$10,16\ K^- p \to K^- \pi^+ n$
0.54 ±0.16	DEHM 74	DBC	0	$4.6\ K^+ N$
0.47 ±0.08	AGUILAR-... 71B	HBC		$3.9,4.6\ K^- p$
0.47 ±0.10	BASSANO 67	HBC	−0	$4.6,5.0\ K^- p$
0.45 ±0.13	BADIER 65C	HBC	−	$3\ K^- p$

$\Gamma(K\omega)/\Gamma(K\pi)$ Γ_5/Γ_1

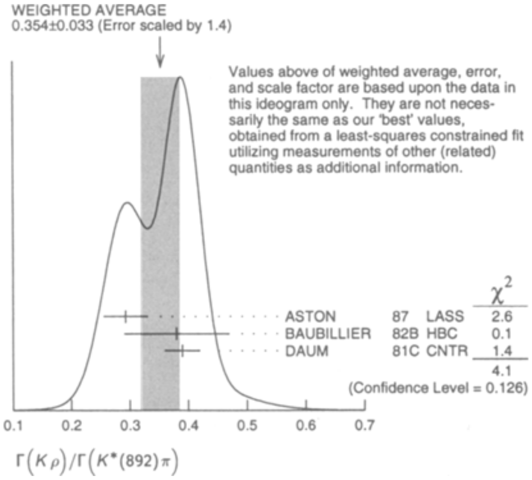
VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.069±0.017 OUR FIT				
0.070±0.035 OUR AVERAGE				
0.05 ±0.04	AGUILAR-... 71B	HBC		$3.9,4.6\ K^- p$
0.13 ±0.07	BASSOMPIE... 69	HBC	0	$5\ K^+ p$

$\Gamma(K\rho)/\Gamma(K\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.174±0.017 OUR FIT	Error includes scale factor of 1.2.			
$0.150^{+0.029}_{-0.017}$ OUR AVERAGE				
0.18 ±0.05	ASTON 84B	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$
$0.02\ ^{+0.10}_{-0.02}$	DEHM 74	DBC	0	$4.6\ K^+ N$
0.16 ±0.05	AGUILAR-... 71B	HBC		$3.9,4.6\ K^- p$
0.14 ±0.10	BASSANO 67	HBC	−0	$4.6,5.0\ K^- p$
0.14 ±0.07	BADIER 65C	HBC	−	$3\ K^- p$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_4/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.350±0.031 OUR FIT	Error includes scale factor of 1.4.			
0.354±0.033 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
0.293±0.032±0.020	ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
0.38 ±0.09	BAUBILLIER 82B	HBC	0	$8.25\ K^- p \to N K_S^0 \pi\pi$
0.39 ±0.03	DAUM 81C	CNTR		$63\ K^- p \to K^- 2\pi p$



$\Gamma(K\omega)/\Gamma(K^*(892)\pi)$ Γ_5/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.118±0.034 OUR FIT				
0.10 ±0.04	FIELD 67	HBC	−	$3.8\ K^- p$

$\Gamma(K\eta)/\Gamma(K^*(892)\pi)$ Γ_7/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
$0.006^{+0.014}_{-0.004}$ OUR FIT	Error includes scale factor of 1.2.			
0.07 ±0.04	FIELD 67	HBC	−	$3.8\ K^- p$

$\Gamma(K\eta)/\Gamma(K\pi)$ Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
$0.0030^{+0.0068}_{-0.0020}$ OUR FIT		Error includes scale factor of 1.3.			
0 ±0.0066		[13] ASTON 88B	LASS	−	$11\ K^- p \to K^- \eta p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	95	AGUILAR-... 71B	HBC		$3.9,4.6\ K^- p$
<0.065		[14] BASSOMPIE... 69	HBC		$5.0\ K^+ p$
<0.02		BISHOP 69	HBC		$3.5\ K^+ p$

$\Gamma(K^*(892)\pi\pi)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.134±0.022 OUR FIT				
0.12 ±0.04	[15] GOLDBERG 76	HBC	−	$3\ K^- p \to p \overline{K}^0 \pi\pi\pi$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.27±0.05 OUR FIT				
0.21±0.08	[14,15] JONGEJANS 78	HBC	−	$4\ K^- p \to p \overline{K}^0 \pi\pi\pi$

$\Gamma(K\omega\pi)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.72	95	0	JONGEJANS 78	HBC	$4\ K^- p \to p \overline{K}^0 4\pi$

[12] From phase shift analysis.

[13] ASTON 88B quote < 0.0092 at CL=95%. We convert this to a central value and 1 sigma error in order to be abe to use it in our constrained fit.

[14] Restated by us.

[15] Assuming $\pi\pi$ system has isospin 1, which is supported by the data.

$K_2^*(1430)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
CARLSMITH	87	PR D36 3502	+Bernstein, Bock, Coupal, Peyaud, Turlay+	(EFI, SACL)
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
CIHANGIR	82	PL 117B 123	+Berg, Biel, Chandlee+	(FNAL, MINN, ROCH)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ASTON	81C	PL 106B 235	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC)
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MCGI, CARL, DURH+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
GOLDBERG	76	LNC 17 253		(HAIF)
HENDRICK	76	NP B112 189	+Vignaud, Burlaud+	(MONS, SACL, PARIS, BELG)
LAUSCHER	75	NP B86 189	+Otter, Wieczorek+	(ABCLV Collab.) JP
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
DEHM	74	NP B75 47	+Goebel, Wittek+	(MPIM, BRUX, MONS, CERN)
LINGLIN	73	NP B55 408		(CERN)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
BARNHAM	71C	NP B28 171	+Colley, Jobes, Griffiths, Hughes+	(BIRM, GLAS)
CORDS	71	PR D4 1974	+Carmony, Erwin, Meiere+	(PURD, UCD, IUPU)
BASSOMPIE...	69	NP B13 189	Bassompierre+	(CERN, BRUX) JP
BISHOP	69	NP B9 403	+Goshaw, Erwin, Walker	(WISC)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
LIND	69	NP B14 1	+Alexander, Firestone, Fu, Goldhaber	(LRL) JP
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
Also	67	Thesis	Schweingruber	(NWES, NWES)
BASSANO	67	PRL 19 968	+Goldberg, Goz, Barnes, Leitner+	(BNL, SYRA)
FIELD	67	PL 24B 638	+Hendricks, Piccioni, Yager	(UCSD)
BADIER	65C	PL 19 612	+Demoulin, Goldberg+	(EPOL, SACL, AMST)

OTHER RELATED PAPERS

ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
CHUNG	65	PRL 15 325	+Dahl, Hardy, Hess, Jacobs, Kirz	(LRL)
FOCARDI	65	PL 16 351	+Ranzi, Serra+	(BGNA, SACL)
HAQUE	65	PL 14 338	Hague+	
HARDY	65	PRL 14 401	+Chung, Dahl, Hess, Kirz, Miller	(LRL)

$K(1460)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Observed in $K\pi\pi$ partial-wave analysis.

$K(1460)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^\pm 2\pi p$

[1] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^\pm 2\pi p$

[2] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	seen
Γ_2	$K\rho$	seen
Γ_3	$K_0^*(1430)\pi$	seen

$K(1460)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 109	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 34	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$\Gamma(K_0^*(1430)\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 117	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$K(1460)$ REFERENCES

DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
BRANDENB...	76B	PRL 36 1239	Brandenburg, Carnegie, Cashmore+	(SLAC) JP

OTHER RELATED PAPERS

BARNES	82	PL B116 365	+Close	(RHEL)
TANIMOTO	82	PL 116B 198		(BIEL)
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)

$K_2(1580)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^-\pi^+\pi^-$ system. Needs confirmation.

$K_2(1580)$ MASS

VALUE (MeV)	DOCUMENT ID		CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1580	OTTER	79	−	10,14,16 $K^- p$

$K_2(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID		CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 110	OTTER	79	−	10,14,16 $K^- p$

$K_2(1580)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	seen
Γ_2	$K_2^*(1430)\pi$	possibly seen

$K_2(1580)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	OTTER	79	HBC	−	10,14,16 $K^- p$

$\Gamma(K_2^*(1430)\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	OTTER	79	HBC	−	10,14,16 $K^- p$

$K_2(1580)$ REFERENCES

OTTER	79	NP B147 1	+Rudolph+	(AACH3, BERL, CERN, LOIC, WIEN) JP

$K_1(1650)$

$I(J^P) = \frac{1}{2}(1^+)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems ($K^+\phi$, $K\pi\pi$) reported in partial-wave analysis in the 1600–1900 mass region.

$K_1(1650)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1650±50	FRAME	86	OMEG	+	$13\ K^+p \to \phi K^+p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1840	ARMSTRONG	83	OMEG	−	$18.5\ K^-p \to 3Kp$
~ 1800	DAUM	81C	CNTR	−	$63\ K^-p \to K^-2\pi p$

$K_1(1650)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150±50	FRAME	86	OMEG	+	$13\ K^+p \to \phi K^+p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	DAUM	81C	CNTR	−	$63\ K^-p \to K^-2\pi p$

$K_1(1650)$ DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$K\phi$

$K_1(1650)$ REFERENCES

FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, CURIN+)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$K^*(1680)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1680)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1717±27 OUR AVERAGE	Error includes scale factor of 1.4.				
1677±10±32	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
1735±10±20	ASTON	87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1678±64	BIRD	89	LASS	−	$11\ K^-p \to \overline{K}^0\pi^-p$
1800±70	ETKIN	80	MPS	0	$6\ K^-p \to \overline{K}^0\pi^+\pi^-n$
~ 1650	ESTABROOKS	78	ASPK	0	$13\ K^\pm p \to K^\pm\pi^\pm n$

$K^*(1680)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
322±110 OUR AVERAGE	Error includes scale factor of 4.2.				
205± 16±34	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
423± 18±30	ASTON	87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
454±270	BIRD	89	LASS	−	$11\ K^-p \to \overline{K}^0\pi^-p$
170± 30	ETKIN	80	MPS	0	$6\ K^-p \to \overline{K}^0\pi^+\pi^-n$
250 to 300	ESTABROOKS	78	ASPK	0	$13\ K^\pm p \to K^\pm\pi^\pm n$

$K^*(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(38.7 ± 2.5) %
Γ_2	$K\rho$	$(31.4^{+4.7}_{-2.1})$ %
Γ_3	$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_2 & -36 & \\ x_3 & -39 & -72 \\ \hline & x_1 & x_2 \end{array}$$

$K^*(1680)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.387±0.026 OUR FIT					
0.388±0.014±0.022	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ **Γ_1/Γ_3**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.30^{+0.23}_{-0.14}$ OUR FIT					
2.8 ±1.1	ASTON	84	LASS	0	$11\ K^-p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K\pi)$ **Γ_2/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$0.81^{+0.14}_{-0.09}$ OUR FIT					
1.2 ±0.4	ASTON	84	LASS	0	$11\ K^-p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ **Γ_2/Γ_3**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.05^{+0.27}_{-0.11}$ OUR FIT					
$0.97\pm0.09^{+0.30}_{-0.10}$	ASTON	87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$

$K^*(1680)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC) JP

$K_2(1770)$

$I(J^P) = \frac{1}{2}(2^-)$

THE $K_2(1770)$ AND THE $K_2(1820)$

A partial-wave analysis of the $K^-\omega$ system based on about 100,000 $K^-p \to K^-\omega p$ events (ASTON 93) gives evidence for two $q\bar{q}$ D-wave states near 1.8 GeV. A previous analysis based on about 200,000 diffractively produced $K^-p \to K^-\pi^+\pi^-p$ events (DAUM 81) gave evidence for two $J^P = 2^-$ states in this region, with masses ~ 1780 MeV and ~ 1840 MeV and widths ~ 200 MeV, in good agreement with the results of ASTON 93. In contrast, the masses obtained using a single resonance do not agree well: ASTON 93 obtains 1728 ± 7 MeV, while DAUM 81 estimates ~ 1820 MeV. We conclude that there are indeed two K_2 resonances here.

We list under the $K_2(1770)$ other measurements that do not resolve the two-resonance structure of the enhancement.

$K_2(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1773± 8		[1] ASTON 93	LASS		$11 K^- p \to K^- \omega p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1810±20		FRAME 86	OMEG	+	$13\ K^+ p \to \phi K^+ p$
~ 1730		ARMSTRONG 83	OMEG	–	$18.5\ K^- p \to 3K p$
~ 1780		[2] DAUM 81C	CNTR	–	$63\ K^- p \to K^- 2\pi p$
1710±15	60	CHUNG 74	HBC	–	$7.3\ K^- p \to K^- \omega p$
1767± 6		BLIEDEN 72	MMS	–	11–16 $K^- p$
1730±20	306	[3] FIRESTONE 72B	DBC	+	$12\ K^+ d$
1765±40		[4] COLLEY 71	HBC	+	$10\ K^+ p \to K 2\pi N$
1740		DENEGRI 71	DBC	–	$12.6\ K^- d \to \overline{K} 2\pi d$
1745±20		AGUILAR-... 70C	HBC	–	$4.6\ K^- p$
1780±15		BARTSCH 70C	HBC	–	$10.1\ K^- p$
1760±15		LUDLAM 70	HBC	–	$12.6\ K^- p$

[1] From a partial wave analysis of the $K^- \omega$ system.
[2] From a partial wave analysis of the $K^- 2\pi$ system.
[3] Produced in conjunction with excited deuteron.
[4] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
186±14		[5] ASTON 93	LASS		$11 K^- p \to K^- \omega p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
140±40		FRAME 86	OMEG	+	$13\ K^+ p \to \phi K^+ p$
~ 220		ARMSTRONG 83	OMEG	–	$18.5\ K^- p \to 3K p$
~ 210		[6] DAUM 81C	CNTR	–	$63\ K^- p \to K^- 2\pi p$
110±50	60	CHUNG 74	HBC	–	$7.3\ K^- p \to K^- \omega p$
100±26		BLIEDEN 72	MMS	–	11–16 $K^- p$
210±30	306	[7] FIRESTONE 72B	DBC	+	$12\ K^+ d$
90±70		[8] COLLEY 71	HBC	+	$10\ K^+ p \to K 2\pi N$
130		DENEGRI 71	DBC	–	$12.6\ K^- d \to \overline{K} 2\pi d$
100±50		AGUILAR-... 70C	HBC	–	$4.6\ K^- p$
138±40		BARTSCH 70C	HBC	–	$10.1\ K^- p$
50^{+40}_{-20}		LUDLAM 70	HBC	–	$12.6\ K^- p$

[5] From a partial wave analysis of the $K^- \omega$ system.
[6] From a partial wave analysis of the $K^- 2\pi$ system.
[7] Produced in conjunction with excited deuteron.
[8] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi\pi$	
Γ_2	$K_2^*(1430)\pi$	dominant
Γ_3	$K^*(892)\pi$	seen
Γ_4	$K f_2(1270)$	seen
Γ_5	$K\phi$	seen
Γ_6	$K\omega$	seen

$K_2(1770)$ BRANCHING RATIOS

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ **Γ_2/Γ_1**

$(K_2^*(1430) \to K\pi)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.03	DAUM 81C	CNTR		$63\ K^- p \to K^- 2\pi p$
~ 1.0	[9] FIRESTONE 72B	DBC	+	$12\ K^+ d$
<1.0	COLLEY 71	HBC		$10\ K^+ p$
0.2 ±0.2	AGUILAR-... 70C	HBC	–	$4.6\ K^- p$
<1.0	BARTSCH 70C	HBC	–	$10.1\ K^- p$
1.0	BARBARO-... 69	HBC	+	$12.0\ K^+ p$

[9] Produced in conjunction with excited deuteron.

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ **Γ_3/Γ_1**

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 0.23	DAUM 81C	CNTR	$63\ K^- p \to K^- 2\pi p$

$\Gamma(K f_2(1270))/\Gamma(K\pi\pi)$ **Γ_4/Γ_1**

$(f_2(1270) \to \pi\pi)$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 0.74	DAUM 81C	CNTR	$63\ K^- p \to K^- 2\pi p$

$\Gamma(K\phi)/\Gamma_{\text{total}}$ **Γ_5/Γ**

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	ARMSTRONG 83	OMEG	–	$18.5\ K^- p \to K^- \phi N$

$\Gamma(K\omega)/\Gamma_{\text{total}}$ **Γ_6/Γ**

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	OTTER 81	HBC	±	8.25,10,16 $K^{\pm} p$
seen	CHUNG 74	HBC	–	$7.3\ K^- p \to K^- \omega p$

$K_2(1770)$ REFERENCES

ASTON	93	PL B308 186	+Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, CURIN+)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
OTTER	81	NP B181 1		(AACH3, BERL, LOIC, VIEN, BIRM, BELG, CERN+)
CHUNG	74	PL 51B 413	+Eisner, Protopopescu, Samios, Strand	(BNL)
BLIEDEN	72	PL 39B 668	+Finocchiaro, Bowen, Earles+	(STON, NEAS)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)
COLLEY	71	NP B26 71	+Jobes, Kenyon, Pathak, Hughes+	(BIRM, GLAS)
DENEGRI	71	NP B28 13	+Antich, Callahan, Carson, Chien, Cox+	(JHU) JP
AGUILAR-...	70C	PRL 25 54	Aguilar-Benitez, Barnes, Bassano, Chung+	(BNL)
BARTSCH	70C	PL 33B 186	+Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN)
LUDLAM	70	PR D2 1234	+Sandweiss, Slaughter	(YALE)
BARBARO-...	69	PRL 22 1207	Barbaro-Galtieri, Davis, Flatte+	(LRL)

OTHER RELATED PAPERS

BERLINGHIERI	67	PRL 18 1087	+Farber, Ferbel, Forman	(ROCH) I
CARMONY	67	PRL 18 615	+Hendricks, Lander	(UCSD)
JOBES	67	PL 26B 49	+Bassompierre, DeBaere+	(BIRM, CERN, BRUX)
BARTSCH	66	PL 22 357	+Deutschmann+	(AACH, BERL, CERN+)

$K_3^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

$K_3^*(1780)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1776± 7 OUR AVERAGE	Error includes scale factor of 1.1.				
1781± 8± 4		[1] ASTON 88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
1740±14±15		[1] ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1779±11		[2] BALDI 76	SPEC	+	$10\ K^+ p \to K^0 \pi^+ p$
1776±26		[3] BRANDENB... 76D	ASPK	0	$13\ K^{\pm} p \to K^{\pm} \pi^{\mp} N$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1720±10±15	6111	[4] BIRD 89	LASS	–	$11\ K^- p \to \overline{K}^0 \pi^- p$
1749±10		ASTON 88B	LASS	–	$11\ K^- p \to K^- \eta p$
1780± 9	300	BAUBILLIER 84B	HBC	–	$8.25\ K^- p \to \overline{K}^0 \pi^- p$
1790±15		BAUBILLIER 82B	HBC	0	$8.25\ K^- p \to K_S^0 2\pi N$
1784± 9	2060	CLELAND 82	SPEC	±	$50\ K^+ p \to K_S^0 \pi^{\pm} p$
1786±15		[5] ASTON 81D	LASS	0	$11\ K^- p \to K^- \pi^+ n$
1762± 9	190	TOAFF 81	HBC	–	$6.5\ K^- p \to \overline{K}^0 \pi^- p$
1850±50		ETKIN 80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^-$
1812±28		BEUSCH 78	OMEG		$10\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1786± 8		CHUNG 78	MPS	0	$6\ K^- p \to K^- \pi^+ n$

[1] From energy-independent partial-wave analysis.
[2] From a fit to Y_6^2 moment. $J^P = 3^-$ found.
[3] Confirmed by phase shift analysis of ESTABROOKS 78, yields $J^P = 3^-$.
[4] From a partial wave amplitude analysis.
[5] From a fit to the Y_6^0 moment.

$K_3^*(1780)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
159±21 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
203±30± 8		[6] ASTON 88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
171±42±20		[6] ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
135±22		[7] BALDI 76	SPEC	+	$10\ K^+ p \to K^0 \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
187±31±20	6111	[8] BIRD 89	LASS	–	$11\ K^- p \to \overline{K}^0 \pi^- p$
193^{+51}_{-37}		ASTON 88B	LASS	–	$11\ K^- p \to K^- \eta p$
99±30	300	BAUBILLIER 84B	HBC	–	$8.25\ K^- p \to \overline{K}^0 \pi^- p$
~ 130		BAUBILLIER 82B	HBC	0	$8.25\ K^- p \to K_S^0 2\pi N$
191±24	2060	CLELAND 82	SPEC	±	$50\ K^+ p \to K_S^0 \pi^{\pm} p$
225±60		[9] ASTON 81D	LASS	0	$11\ K^- p \to K^- \pi^+ n$
~ 80	190	TOAFF 81	HBC	–	$6.5\ K^- p \to \overline{K}^0 \pi^- p$
240±50		ETKIN 80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^-$
181±44		[10] BEUSCH 78	OMEG		$10\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
96±31		CHUNG 78	MPS	0	$6\ K^- p \to K^- \pi^+ n$
270±70		[11] BRANDENB... 76D	ASPK	0	$13\ K^{\pm} p \to K^{\pm} \pi^{\mp} N$

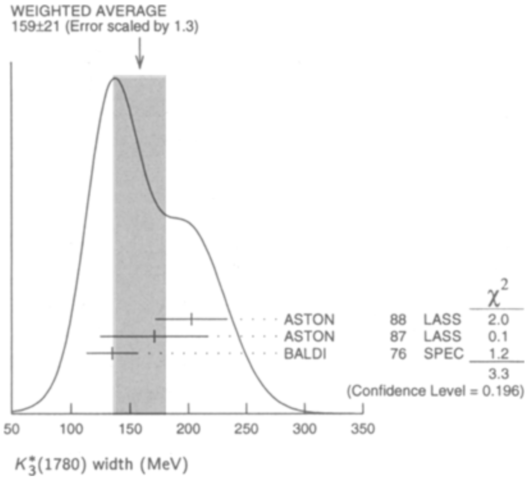
[6] From energy-independent partial-wave analysis.
[7] From a fit to Y_6^2 moment. $J^P = 3^-$ found.

[8] From a partial wave amplitude analysis.

[9] From a fit to Y_6^0 moment.

[10] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[11] ESTABROOKS 78 find that BRANDENBURG 76D data are consistent with 175 MeV width. Not averaged.



$K_3^*(1780)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\rho$	(31 ± 9) %	
Γ_2	$K^*(892)\pi$	(20 ± 5) %	
Γ_3	$K\pi$	(18.8± 1.0) %	
Γ_4	$K\eta$	(30 ±13) %	
Γ_5	$K_2^*(1430)\pi$	< 16 %	95%

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 4 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 0.0 for 1 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc} x_2 & 85 & & \\ x_3 & 18 & 21 & \\ x_4 & -98 & -94 & -27 \\ \hline & x_1 & x_2 & x_3 \end{array}$$

$K_3^*(1780)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
1.52±0.23 OUR FIT				
1.52±0.21±0.10	ASTON 87	LASS	0	11 $K^-p \rightarrow \overline{K}^0\pi^+\pi^-n$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
1.09±0.26 OUR FIT				
1.09±0.26	ASTON 84B	LASS	0	11 $K^-p \rightarrow \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.188±0.010 OUR FIT				
0.188±0.010 OUR AVERAGE				
0.187±0.008±0.008	ASTON 88	LASS	0	11 $K^-p \rightarrow K^-\pi^+n$
0.19 ±0.02	ESTABROOKS 78	ASPK	0	13 $K^{\pm}p \rightarrow K\pi N$

$\Gamma(K\eta)/\Gamma(K\pi)$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
1.6 ±0.7 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41±0.050	[12] BIRD 89	LASS	–	11 $K^-p \rightarrow \overline{K}^0\pi^-p$
0.50±0.18	ASTON 88B	LASS	–	11 $K^-p \rightarrow K^-\eta p$

[12] This result supersedes ASTON 88B.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K^*(892)\pi)$ Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.78	95	ASTON 87	LASS	0	11 $K^-p \rightarrow \overline{K}^0\pi^+\pi^-n$

$K_3^*(1780)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)	
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)	
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)	JP
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)	
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)	
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)	
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)	
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)	
ASTON	81D	PL 99B 502	+Dunwoodie, Durkin, Fieguth+	(SLAC, CARL, OTTA)	JP
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)	
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY)	JP
BEUSCH	78	PL 74B 282	+Birman, Konigs, Otter+	(CERN, AACH3, ETH)	JP
CHUNG	78	PRL 40 355	+Etkin+	(BNL, BRAN, CUNY, MASA, PENN)	JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC)	JP
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MCGI, CARL, DURH+)	
BALDI	76	PL 63B 344	+Boehringer, Dorsaz, Hungerbuhler+	(GEVA)	JP
BRANDENB...	76D	PL 60B 478	Brandenburg, Carnegie, Cashmore+	(SLAC)	JP

OTHER RELATED PAPERS

AGUILAR-...	73	PRL 30 672	Aguilar-Benitez, Chung, Eisner+	(BNL)
WALUCH	73	PR D8 2837	+Flatte, Friedman	(LBL)
CARMONY	71	PRL 27 1160	+Cords, Clopp, Erwin, Meiere+	(PURD, UCD, IUPU)
FIRESTONE	71	PL 36B 513	+Goldhaber, Lissauer, Trilling	(LBL)

$K_2(1820)$

$I(J^P) = \frac{1}{2}(2^-)$

Observed by ASTON 93 from a partial wave analysis of the $K^-\omega$ system. See mini-review under $K_2(1770)$.

$K_2(1820)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1816±13	[1] ASTON 93	LASS	11 $K^-p \rightarrow K^-\omega p$
~ 1840	[2] DAUM 81C	CNTR	63 $K^-p \rightarrow K^-2\pi p$

[1] Fron a partial wave analysis of the $K^-\omega$ system.

[2] From a partial wave analysis of the $K^-2\pi$ system.

$K_2(1820)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
276±35	[3] ASTON 93	LASS	11 $K^-p \rightarrow K^-\omega p$
~ 230	[4] DAUM 81C	CNTR	63 $K^-p \rightarrow K^-2\pi p$

[3] Fron a partial wave analysis of the $K^-\omega$ system.

[4] From a partial wave analysis of the $K^-2\pi$ system.

$K_2(1820)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi\pi$	
Γ_2	$K_2^*(1430)\pi$	seen
Γ_3	$K^*(892)\pi$	seen
Γ_4	$Kf_2(1270)$	seen
Γ_5	$K\omega$	seen

$K_2(1820)$ BRANCHING RATIOS

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 0.77	DAUM 81C	CNTR	63$K^-p \rightarrow \overline{K}2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 0.05	DAUM 81C	CNTR	63$K^-p \rightarrow \overline{K}2\pi p$

$\Gamma(Kf_2(1270))/\Gamma(K\pi\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 0.18	DAUM 81C	CNTR	63$K^-p \rightarrow \overline{K}2\pi p$

$K_2(1820)$ REFERENCES

ASTON	93	PL B308 186	+Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$K(1830)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of $K^- \phi$ system. Needs confirmation.

$K(1830)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1830	ARMSTRONG 83	OMEG	−	18.5 $K^- p \rightarrow 3Kp$

$K(1830)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 250	ARMSTRONG 83	OMEG	−	18.5 $K^- p \rightarrow 3Kp$

$K(1830)$ DECAY MODES

	Mode
Γ_1	$K\phi$

$K(1830)$ REFERENCES

ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, CURIN+) JP

$K_0^*(1950)$

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^- \pi^+$ system. Needs confirmation.

$K_0^*(1950)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1945±10±20	[1] ASTON 88	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1820±40	[2] ANISOVICH 97C	RVUE		11 $K^- p \rightarrow K^- \pi^+ n$

[1] We take the central value of the two solutions and the larger error given.

[2] T-matrix pole. Reanalysis of ASTON 88 data.

$K_0^*(1950)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
201± 34±79	[3] ASTON 88	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
250±100	[4] ANISOVICH 97C	RVUE		11 $K^- p \rightarrow K^- \pi^+ n$

[3] We take the central value of the two solutions and the larger error given.

[4] T-matrix pole. Reanalysis of ASTON 88 data.

$K_0^*(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(52±14) %

$K_0^*(1950)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.52±0.08±0.12	[5] ASTON 88	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$

[5] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ REFERENCES

ANISOVICH 97C PL B413 137
ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)

$K_2^*(1980)$

$I(J^P) = \frac{1}{2}(2^+)$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$K_2^*(1980)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1973± 8±25		ASTON 87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1978±40	241±47	BIRD 89	LASS	−	11 $K^- p \rightarrow \overline{K}^0 \pi^- p$

$K_2^*(1980)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
373±33±60		ASTON 87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
398±47	241±47	BIRD 89	LASS	−	11 $K^- p \rightarrow \overline{K}^0 \pi^- p$

$K_2^*(1980)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$

$K_2^*(1980)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ **Γ_2/Γ_1**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1.49±0.24±0.09	ASTON 87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)

$K_4^*(2045)$

$I(J^P) = \frac{1}{2}(4^+)$

$K_4^*(2045)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
2045± 9 OUR AVERAGE		Error includes scale factor of 1.1.			
2062± 14±13		[1] ASTON 86	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
2039± 10	400	[2,3] CLELAND 82	SPEC	±	50 $K^+ p \rightarrow K_S^0 \pi^\pm p$
2070^{+100}_{-40}		[4] ASTON 81C	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2079± 7	431	TORRES 86	MPSF		400 $pA \rightarrow 4KX$
2088± 20	650	BAUBILLIER 82	HBC	−	8.25 $K^- p \rightarrow K_S^0 \pi^- p$
2115± 46	488	CARMONY 77	HBC	0	9 $K^+ d \rightarrow K^+ \pi$'s X

[1] From a fit to all moments.

[2] From a fit to 8 moments.

[3] Number of events evaluated by us.

[4] From energy-independent partial-wave analysis.

$K_4^*(2045)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
198± 30 OUR AVERAGE					
221± 48±27		[5] ASTON 86	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
189± 35	400	[6,7] CLELAND 82	SPEC	±	50 $K^+ p \rightarrow K_S^0 \pi^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
61± 58	431	TORRES 86	MPSF		400 $pA \rightarrow 4KX$
170^{+100}_{-50}	650	BAUBILLIER 82	HBC	−	8.25 $K^- p \rightarrow K_S^0 \pi^- p$
240^{+500}_{-100}		[8] ASTON 81C	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$
300±200		CARMONY 77	HBC	0	9 $K^+ d \rightarrow K^+ \pi$'s X

[5] From a fit to all moments.

[6] From a fit to 8 moments.

[7] Number of events evaluated by us.

[8] From energy-independent partial-wave analysis.

K_4^*(2045) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(9.9±1.2) %
Γ_2	$K^*(892)\pi\pi$	(9 ±5) %
Γ_3	$K^*(892)\pi\pi\pi$	(7 ±5) %
Γ_4	$\rho K\pi$	(5.7±3.2) %
Γ_5	$\omega K\pi$	(5.0±3.0) %
Γ_6	$\phi K\pi$	(2.8±1.4) %
Γ_7	$\phi K^*(892)$	(1.4±0.7) %

K_4^*(2045) BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.099±0.012	ASTON	88	LASS	0	11 $K^-p \to K^-\pi^+n$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ **Γ_2/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.89±0.53	BAUBILLIER	82	HBC	−	8.25 $K^-p \to pK_S^0 3\pi$

$\Gamma(K^*(892)\pi\pi\pi)/\Gamma(K\pi)$ **Γ_3/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75±0.49	BAUBILLIER	82	HBC	−	8.25 $K^-p \to pK_S^0 3\pi$

$\Gamma(\rho K\pi)/\Gamma(K\pi)$ **Γ_4/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.58±0.32	BAUBILLIER	82	HBC	−	8.25 $K^-p \to pK_S^0 3\pi$

$\Gamma(\omega K\pi)/\Gamma(K\pi)$ **Γ_5/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.50±0.30	BAUBILLIER	82	HBC	−	8.25 $K^-p \to pK_S^0 3\pi$

$\Gamma(\phi K\pi)/\Gamma_{\text{total}}$ **Γ_6/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.028±0.014	[9] TORRES	86	MPSF	400 $pA \to 4KX$

$\Gamma(\phi K^*(892))/\Gamma_{\text{total}}$ **Γ_7/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.014±0.007	[9] TORRES	86	MPSF	400 $pA \to 4KX$

[9] Error determination is model dependent.

K_4^*(2045) REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
TORRES 86 PR 34 707 +Lai+ (VPI, ARIZ, FNAL, FSU, NDAM, TUFTS+)
BAUBILLIER 82 PL 118B 447 +Burns+ (BIRM, CERN, GLAS, MSU, CURIN)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81C PL 106B 235 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
CARMONY 77 PR D16 1251 +Clopp, Lander, Meiere, Yen+ (PURD, UCD, IUPU)

OTHER RELATED PAPERS

ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
CARMONY 71 PRL 27 1160 +Cords, Clopp, Erwin, Meiere+ (PURD, UCD, IUPU)

$K_2(2250)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems reported in the 2150–2260 MeV region, as well as enhancements seen in the antihyperon-nucleon system, either in the mass spectra or in the $J^P = 2^-$ wave.

K_2(2250) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2247±17 OUR AVERAGE						
2200±40		[1] ARMSTRONG	83C	OMEG	−	18 $K^-p \to \Lambda\bar{p}X$
2235±50		[1] BAUBILLIER	81	HBC	−	8 $K^-p \to \Lambda\bar{p}X$
2260±20		[1] CLELAND	81	SPEC	±	50 $K^+p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2147± 4	37	CHLIAPNIK...	79	HBC	+	32 $K^+p \to \bar{\Lambda}pX$
2240±20	20	LISSAUER	70	HBC		9 K^+p

[1] $J^P = 2^-$ from moments analysis.

K_2(2250) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
180±30 OUR AVERAGE	Error includes scale factor of 1.4.					
150±30		[2] ARMSTRONG	83C	OMEG	−	18 $K^-p \to \Lambda\bar{p}X$
210±30		[2] CLELAND	81	SPEC	±	50 $K^+p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 200		[2] BAUBILLIER	81	HBC	−	8 $K^-p \to \Lambda\bar{p}X$
~ 40	37	CHLIAPNIK...	79	HBC	+	32 $K^+p \to \bar{\Lambda}pX$
80±20	20	LISSAUER	70	HBC		9 K^+p

[2] $J^P = 2^-$ from moments analysis.

K_2(2250) DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$p\bar{\Lambda}$

K_2(2250) REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, CURIN+)
BAUBILLIER 81 NP B183 1 + (BIRM, CERN, GLAS, MSU, CURIN) JP
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH) JP
CHLIAPNIK... 79 NP B158 253 Chliapnikov, Gerdyukov+ (CERN, BELG, MONS)
LISSAUER 70 NP B18 491 +Alexander, Firestone, Goldhaber (LBL)

OTHER RELATED PAPERS

ALEXANDER 68B PRL 20 755 +Firestone, Goldhaber, Shen (LRL)

$K_3(2320)$

$I(J^P) = \frac{1}{2}(3^+)$

OMITTED FROM SUMMARY TABLE

Seen in the $J^P = 3^+$ wave of the antihyperon-nucleon system. Needs confirmation.

K_3(2320) MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2324±24 OUR AVERAGE					
2330±40	[1] ARMSTRONG	83C	OMEG	−	18 $K^-p \to \Lambda\bar{p}X$
2320±30	[1] CLELAND	81	SPEC	±	50 $K^+p \to \Lambda\bar{p}X$

[1] $J^P = 3^+$ from moments analysis.

K_3(2320) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150±30	[2] ARMSTRONG	83C	OMEG	−	18 $K^-p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[2] CLELAND	81	SPEC	±	50 $K^+p \to \Lambda\bar{p}X$

[2] $J^P = 3^+$ from moments analysis.

K_3(2320) DECAY MODES

	Mode
Γ_1	$p\bar{\Lambda}$

K_3(2320) REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, CURIN+)
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

$\boxed{K_5^*(2380)}$

$I(J^P) = \frac{1}{2}(5^-)$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$K_5^*(2380)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2382±14±19	[1] ASTON	86	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$

[1] From a fit to all the moments.

$K_5^*(2380)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
178±37±32	[2] ASTON	86	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$

[2] From a fit to all the moments.

$K_5^*(2380)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(6.1 ± 1.2) %

$K_5^*(2380)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.061±0.012	ASTON	88	LASS	0	11 $K^- p \rightarrow K^- \pi^+ n$

$K_5^*(2380)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)

$\boxed{K_4(2500)}$

$I(J^P) = \frac{1}{2}(4^-)$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$K_4(2500)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2490±20	[1] CLELAND	81	SPEC	±	50 $K^+ p \rightarrow \Lambda\overline{p}$

[1] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[2] CLELAND	81	SPEC	±	50 $K^+ p \rightarrow \Lambda\overline{p}$

[2] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ DECAY MODES

	Mode
Γ_1	$p\overline{\Lambda}$

$K_4(2500)$ REFERENCES

CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

$\boxed{K(3100)}$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several ($\Lambda\overline{p}$ + pions) and ($\overline{\Lambda}p$ + pions) states in Σ^- Be reactions Needs confirmation. by BOURQUIN 86 and in np and nA reactions by ALEEV 93. Not seen by BOEHNLEIN 91. If due to strong decays, this state has exotic quantum numbers (B=0,Q=+1,S=−1 for $\Lambda\overline{p}\pi^+\pi^+$ and $I \geq 3/2$ for $\Lambda\overline{p}\pi^-$). Needs confirmation.

$K(3100)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 3100 OUR ESTIMATE	

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3054±11 OUR AVERAGE				
3060± 7±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+$
3056± 7±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-$
3055± 8±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^-$
3045± 8±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3059±11 OUR AVERAGE				
3067± 6±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+$
3060± 8±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^-$
3055± 7±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-\pi^-$
3052± 8±20	[1] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3105±30	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+$
3115±30	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3095±30	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+\pi^-$

[1] Supersedes ALEEV 90.

$K(3100)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
42±16	[2] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+$
36±15	[2] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-$
50±18	[2] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^-$
30±15	[2] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
22± 8		[2] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+$
28±12		[2] ALEEV	93	BIS2	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^-$
32±15		[2] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-\pi^-$
30±15		[2] ALEEV	93	BIS2	$K(3100) \rightarrow \overline{\Lambda}p\pi^-\pi^+$
<30	90	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+$
<80	90	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<30	90	BOURQUIN	86	SPEC	$K(3100) \rightarrow \Lambda\overline{p}\pi^+\pi^+\pi^-$

[2] Supersedes ALEEV 90.

$K(3100)$ DECAY MODES

	Mode
Γ_1	$K(3100)^0 \rightarrow \Lambda\overline{p}\pi^+$
Γ_2	$K(3100)^{--} \rightarrow \Lambda\overline{p}\pi^-$
Γ_3	$K(3100)^- \rightarrow \Lambda\overline{p}\pi^+\pi^-$
Γ_4	$K(3100)^+ \rightarrow \Lambda\overline{p}\pi^+\pi^+$
Γ_5	$K(3100)^0 \rightarrow \Lambda\overline{p}\pi^+\pi^+\pi^-$
Γ_6	$K(3100)^0 \rightarrow \Sigma(1385)^+\overline{p}$

$\Gamma(\Sigma(1385)^+\overline{p})/\Gamma(\Lambda\overline{p}\pi^+)$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	ALEEV	93	BIS2	$K(3100)^0 \rightarrow \Sigma(1385)^+\overline{p}$

$K(3100)$ REFERENCES

ALEEV 93 PAN 56 1358 +Balandin+ (BIS-2 Collab.)
Translated from YAF 56 100.
BOEHNLEIN 91 NP B21 174 (suppl) +Chung+ (FLOR, BNL, IND, RICE, MASD)
ALEEV 90 ZPHY C47 533 +Arefiev, Balandin+ (BIS-2 Collab.)
BOURQUIN 86 PL B172 113 +Brown+ (GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

CHARMED MESONS
$(C = \pm1)$

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}u$, $D^- = \overline{c}d$, similarly for D^*'s

NOTE ON D MESONS

Written March 1998 by P.R. Burchat (Stanford University).

The new experimental results on charm meson decays reported in this edition are mostly from CLEO II at the e^+e^- storage ring CESR and from the Fermilab fixed-target experiments E687 and E791. A number of searches have been made for rare decays that are potentially sensitive to new physics, such as $D^0\overline{D}^0$ mixing (AITALA 96C and AITALA 98), CP-violating asymmetries in decay rates (AITALA 97B and AITALA 98C), and decays that would signal flavor-changing neutral currents (ADAMOVICH 97 and ALEXOPOULOS 97) or lepton-family number or lepton number violation (FRABETTI 97B). None of the searches has yielded evidence for new physics.

Significant progress has been made in the area of semileptonic charm decays. Five new results on rates for Cabibbo-suppressed semileptonic decays appear in this edition: $D^+ \rightarrow \rho\ell^+\nu_\ell$ from E687 (FRABETTI 97) and E791 (AITALA 97), $D^0 \rightarrow \pi^-\ell^+\nu_\ell$ from E687 (FRABETTI 96B), and $D^+ \rightarrow \pi^0\ell^+\nu_\ell$ and $\eta e^+\nu_e$ from CLEO (BARTELT 97). Our knowledge of the inclusive semileptonic decay rate for the D^0 is greatly improved by new results from ARGUS (ALBRECHT 96C) and CLEO (KUBOTA 96B). The precision of the measurement of the form-factor ratios in the decay $D^+ \rightarrow \overline{K}^{*0}\ell^+\nu_\ell$ has been improved by about a factor of two in a new analysis by E791 (AITALA 98B).

Many new studies of hadronic final states have been made, including measurements of singly and doubly Cabibbo-suppressed D^0 and D^+ decay rates and studies of resonant substructure.

New measurements of the D_s^+ decay constant have been made by the L3 collaboration (ACCIARRI 97F) and the E653 collaboration (KODAMA 96). However, the statistical and systematic uncertainties are still on the order of (10–20)% each. Other new measurements on the D_s^+ front include two inclusive branching fractions by BES (BAI 97 and BAI 98), and the first observation of $D_s^+ \rightarrow \omega\pi^+$ by CLEO (BALEST 97).

$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$D^{\pm}$ MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1869.3 ± 0.5 OUR FIT	Error includes scale factor of 1.1.			
1869.4 ± 0.5 OUR AVERAGE				
1870.0 ± 0.5 ± 1.0	317	BARLAG 90C	ACCM	π^- Cu 230 GeV
1863 ± 4		DERRICK 84	HRS	e^+e^- 29 GeV
1869.4 ± 0.6		[1] TRILLING 81	RVUE	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1875 ± 10	9	ADAMOVICH 87	EMUL	Photoproduction
1860 ± 16	6	ADAMOVICH 84	EMUL	Photoproduction
1868.4 ± 0.5		[1] SCHINDLER 81	MRK2	e^+e^- 3.77 GeV
1874 ± 5		GOLDHABER 77	MRK1	D^0, D^+ recoil spectra
1868.3 ± 0.9		[1] PERUZZI 77	MRK1	e^+e^- 3.77 GeV
1874 ± 11		PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV
1876 ± 15	50	PERUZZI 76	MRK1	$K^{\mp}\pi^{\pm}\pi^{\pm}$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted.

$D^{\pm}$ MEAN LIFE

Measurements with an error $> 0.1\times10^{-12}$ s are omitted from the average, and those with an error $> 0.2 \times 10^{-12}$ s have been omitted from the Listings.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
1.057 ± 0.015 OUR AVERAGE				
1.048 ± 0.015 ± 0.011	9k	FRABETTI 94D	E687	$D^+ \rightarrow K^-\pi^+\pi^+$
1.075 ± 0.040 ± 0.018	2455	FRABETTI 91	E687	γ Be, $D^+ \rightarrow K^-\pi^+\pi^+$
1.03 ± 0.08 ± 0.06	200	ALVAREZ 90	NA14	γ, $D^+ \rightarrow K^-\pi^+\pi^+$
1.05 $^{+0.077}_{-0.072}$	317	[2] BARLAG 90C	ACCM	π^- Cu 230 GeV
1.05 ± 0.08 ± 0.07	363	ALBRECHT 88I	ARG	e^+e^- 10 GeV
1.090 ± 0.030 ± 0.025	2992	RAAB 88	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.12 $^{+0.14}_{-0.11}$	149	AGUILAR-... 87D	HYBR	$\pi^- p$ and pp
1.09 $^{+0.19}_{-0.15}$	59	BARLAG 87B	ACCM	K^- and π^- 200 GeV
1.14 ± 0.16 ± 0.07	247	CSORNA 87	CLEO	e^+e^- 10 GeV
1.09 ± 0.14	74	[3] PALKA 87B	SILI	π Be 200 GeV
0.86 ± 0.13 $^{+0.07}_{-0.03}$	48	ABE 86	HYBR	γp 20 GeV

[2] BARLAG 90C estimates the systematic error to be negligible.

[3] PALKA 87B observes this in $D^+ \rightarrow \overline{K}^*(892)e\nu$.

D^+ DECAY MODES

D^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+ anything	(17.2 ± 1.9) %	
Γ_2	K^- anything	(24.2 ± 2.8) %	S=1.4
Γ_3	$\overline{K}^0$ anything + K^0 anything	(59 ± 7) %	
Γ_4	K^+ anything	(5.8 ± 1.4) %	
Γ_5	η anything	[a] < 13 %	CL=90%
Γ_6	μ^+ anything		
	Leptonic and semileptonic modes		
Γ_7	$\mu^+\nu_\mu$	$< 7.2 \times 10^{-4}$	CL=90%
Γ_8	$\overline{K}^0\ell^+\nu_\ell$	[b] (6.8 ± 0.8) %	
Γ_9	$\overline{K}^0 e^+\nu_e$	(6.7 ± 0.9) %	
Γ_{10}	$\overline{K}^0\mu^+\nu_\mu$	$(7.0 ^{+3.0}_{-2.0})$ %	
Γ_{11}	$K^-\pi^+e^+\nu_e$	$(4.1 ^{+0.9}_{-0.7})$ %	
Γ_{12}	$\overline{K}^*(892)^0 e^+\nu_e \times B(\overline{K}^{*0} \rightarrow K^-\pi^+)$	(3.2 ± 0.33) %	
Γ_{13}	$K^-\pi^+e^+\nu_e$ nonresonant	$< 7 \times 10^{-3}$	CL=90%
Γ_{14}	$K^-\pi^+\mu^+\nu_\mu$	(3.2 ± 0.4) %	S=1.1

In the fit as $\frac{2}{3}\Gamma_{26} + \Gamma_{16}$, where $\frac{2}{3}\Gamma_{26} = \Gamma_{15}$.

Γ_{15}	$\overline{K}^*(892)^0 \mu^+ \nu_\mu$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(2.9 \pm 0.4)\,\%$	
Γ_{16}	$K^- \pi^+ \mu^+ \nu_\mu$ nonresonant		$(2.7 \pm 1.1) \times 10^{-3}$	
Γ_{17}	$\overline{K}^0 \pi^+ \pi^- e^+ \nu_e$			
Γ_{18}	$K^- \pi^+ \pi^0 e^+ \nu_e$			
Γ_{19}	$(\overline{K}^*(892)\pi)^0 e^+ \nu_e$		$< 1.2\,\%$	CL=90%
Γ_{20}	$(\overline{K}\pi\pi)^0 e^+ \nu_e$ non-$\overline{K}^*(892)$		$< 9 \times 10^{-3}$	CL=90%
Γ_{21}	$K^- \pi^+ \pi^0 \mu^+ \nu_\mu$		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{22}	$\pi^0 \ell^+ \nu_\ell$	[c]	$(3.1 \pm 1.5) \times 10^{-3}$	
Γ_{23}	$\pi^+ \pi^- e^+ \nu_e$			

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{24}	$\overline{K}^*(892)^0 \ell^+ \nu_\ell$	[b]	$(4.7 \pm 0.4)\,\%$	
Γ_{25}	$\overline{K}^*(892)^0 e^+ \nu_e$		$(4.8 \pm 0.5)\,\%$	
Γ_{26}	$\overline{K}^*(892)^0 \mu^+ \nu_\mu$		$(4.4 \pm 0.6)\,\%$	S=1.1
Γ_{27}	$\rho^0 e^+ \nu_e$		$(2.2 \pm 0.8) \times 10^{-3}$	
Γ_{28}	$\rho^0 \mu^+ \nu_\mu$		$(2.7 \pm 0.7) \times 10^{-3}$	
Γ_{29}	$\phi e^+ \nu_e$		$< 2.09\,\%$	CL=90%
Γ_{30}	$\phi \mu^+ \nu_\mu$		$< 3.72\,\%$	CL=90%
Γ_{31}	$\eta \ell^+ \nu_\ell$		$< 5 \times 10^{-3}$	CL=90%
Γ_{32}	$\eta'(958) \mu^+ \nu_\mu$		$< 9 \times 10^{-3}$	CL=90%

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

Γ_{33}	$\overline{K}^0 \pi^+$		$(2.89 \pm 0.26)\,\%$	S=1.1
Γ_{34}	$K^- \pi^+ \pi^+$	[d]	$(9.0 \pm 0.6)\,\%$	
Γ_{35}	$\overline{K}^*(892)^0 \pi^+$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(1.27 \pm 0.13)\,\%$	
Γ_{36}	$\overline{K}^*_0(1430)^0 \pi^+$ $\times$ B($\overline{K}^*_0(1430)^0 \to K^- \pi^+$)		$(2.3 \pm 0.3)\,\%$	
Γ_{37}	$\overline{K}^*(1680)^0 \pi^+$ $\times$ B($\overline{K}^*(1680)^0 \to K^- \pi^+$)		$(3.7 \pm 0.8) \times 10^{-3}$	
Γ_{38}	$K^- \pi^+ \pi^+$ nonresonant		$(8.5 \pm 0.8)\,\%$	
Γ_{39}	$\overline{K}^0 \pi^+ \pi^0$	[d]	$(9.7 \pm 3.0)\,\%$	S=1.1
Γ_{40}	$\overline{K}^0 \rho^+$		$(6.6 \pm 2.5)\,\%$	
Γ_{41}	$\overline{K}^*(892)^0 \pi^+$ $\times$ B($\overline{K}^{*0} \to \overline{K}^0 \pi^0$)		$(6.3 \pm 0.4) \times 10^{-3}$	
Γ_{42}	$\overline{K}^0 \pi^+ \pi^0$ nonresonant		$(1.3 \pm 1.1)\,\%$	
Γ_{43}	$K^- \pi^+ \pi^+ \pi^0$	[d]	$(6.4 \pm 1.1)\,\%$	
Γ_{44}	$\overline{K}^*(892)^0 \rho^+$ total $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(1.4 \pm 0.9)\,\%$	
Γ_{45}	$\overline{K}_1(1400)^0 \pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to K^- \pi^+ \pi^0$)		$(2.2 \pm 0.6)\,\%$	
Γ_{46}	$K^- \rho^+ \pi^+$ total		$(3.1 \pm 1.1)\,\%$	
Γ_{47}	$K^- \rho^+ \pi^+$ 3-body		$(1.1 \pm 0.4)\,\%$	
Γ_{48}	$\overline{K}^*(892)^0 \pi^+ \pi^0$ total $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(4.5 \pm 0.9)\,\%$	
Γ_{49}	$\overline{K}^*(892)^0 \pi^+ \pi^0$ 3-body $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(2.8 \pm 0.9)\,\%$	
Γ_{50}	$K^*(892)^- \pi^+ \pi^+$ 3-body $\times$ B($K^{*-} \to K^- \pi^0$)		$(7 \pm 3) \times 10^{-3}$	
Γ_{51}	$K^- \pi^+ \pi^+ \pi^0$ nonresonant	[e]	$(1.2 \pm 0.6)\,\%$	
Γ_{52}	$\overline{K}^0 \pi^+ \pi^+ \pi^-$	[d]	$(7.0 \pm 0.9)\,\%$	
Γ_{53}	$\overline{K}^0 a_1(1260)^+$ $\times$ B($a_1(1260)^+ \to \pi^+ \pi^+ \pi^-$)		$(4.0 \pm 0.9)\,\%$	
Γ_{54}	$\overline{K}_1(1400)^0 \pi^+$ $\times$ B($\overline{K}_1(1400)^0 \to \overline{K}^0 \pi^+ \pi^-$)		$(2.2 \pm 0.6)\,\%$	
Γ_{55}	$K^*(892)^- \pi^+ \pi^+$ 3-body $\times$ B($K^{*-} \to \overline{K}^0 \pi^-$)		$(1.4 \pm 0.6)\,\%$	
Γ_{56}	$\overline{K}^0 \rho^0 \pi^+$ total		$(4.2 \pm 0.9)\,\%$	
Γ_{57}	$\overline{K}^0 \rho^0 \pi^+$ 3-body		$(5 \pm 5) \times 10^{-3}$	
Γ_{58}	$\overline{K}^0 \pi^+ \pi^+ \pi^-$ nonresonant		$(8 \pm 4) \times 10^{-3}$	
Γ_{59}	$K^- \pi^+ \pi^+ \pi^+ \pi^-$	[d]	$(7.2 \pm 1.0) \times 10^{-3}$	
Γ_{60}	$\overline{K}^*(892)^0 \pi^+ \pi^+ \pi^-$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(5.4 \pm 2.3) \times 10^{-3}$	
Γ_{61}	$\overline{K}^*(892)^0 \rho^0 \pi^+$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(1.9^{+1.1}_{-1.0}) \times 10^{-3}$	
Γ_{62}	$\overline{K}^*(892)^0 \pi^+ \pi^+ \pi^-$ no-ρ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(2.9 \pm 1.1) \times 10^{-3}$	
Γ_{63}	$K^- \rho^0 \pi^+ \pi^+$		$(3.1 \pm 0.9) \times 10^{-3}$	
Γ_{64}	$K^- \pi^+ \pi^+ \pi^+ \pi^-$ nonresonant		$< 2.3 \times 10^{-3}$	CL=90%
Γ_{65}	$K^- \pi^+ \pi^+ \pi^0 \pi^0$		$(2.2^{+5.0}_{-0.9})\,\%$	
Γ_{66}	$\overline{K}^0 \pi^+ \pi^+ \pi^- \pi^0$		$(5.4^{+3.0}_{-1.4})\,\%$	
Γ_{67}	$\overline{K}^0 \pi^+ \pi^+ \pi^+ \pi^- \pi^-$		$(8 \pm 7) \times 10^{-4}$	
Γ_{68}	$K^- \pi^+ \pi^+ \pi^+ \pi^- \pi^0$		$(2.0 \pm 1.8) \times 10^{-3}$	
Γ_{69}	$\overline{K}^0 \overline{K}^0 K^+$		$(1.8 \pm 0.8)\,\%$	

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{70}	$\overline{K}^0 \rho^+$		$(6.6 \pm 2.5)\,\%$	
Γ_{71}	$\overline{K}^0 a_1(1260)^+$		$(8.0 \pm 1.7)\,\%$	
Γ_{72}	$\overline{K}^0 a_2(1320)^+$		$< 3 \times 10^{-3}$	CL=90%
Γ_{73}	$\overline{K}^*(892)^0 \pi^+$		$(1.90 \pm 0.19)\,\%$	
Γ_{74}	$\overline{K}^*(892)^0 \rho^+$ total	[e]	$(2.1 \pm 1.3)\,\%$	
Γ_{75}	$\overline{K}^*(892)^0 \rho^+$ *S*-wave	[e]	$(1.6 \pm 1.6)\,\%$	
Γ_{76}	$\overline{K}^*(892)^0 \rho^+$ *P*-wave		$< 1 \times 10^{-3}$	CL=90%
Γ_{77}	$\overline{K}^*(892)^0 \rho^+$ *D*-wave		$(10 \pm 7) \times 10^{-3}$	
Γ_{78}	$\overline{K}^*(892)^0 \rho^+$ *D*-wave longitudinal		$< 7 \times 10^{-3}$	CL=90%
Γ_{79}	$\overline{K}_1(1270)^0 \pi^+$		$< 7 \times 10^{-3}$	CL=90%
Γ_{80}	$\overline{K}_1(1400)^0 \pi^+$		$(4.9 \pm 1.2)\,\%$	
Γ_{81}	$\overline{K}^*(1410)^0 \pi^+$		$< 7 \times 10^{-3}$	CL=90%
Γ_{82}	$\overline{K}^*_0(1430)^0 \pi^+$		$(3.7 \pm 0.4)\,\%$	
Γ_{83}	$\overline{K}^*(1680)^0 \pi^+$		$(1.43 \pm 0.30)\,\%$	
Γ_{84}	$\overline{K}^*(892)^0 \pi^+ \pi^0$ total		$(6.7 \pm 1.4)\,\%$	
Γ_{85}	$\overline{K}^*(892)^0 \pi^+ \pi^0$ 3-body	[e]	$(4.2 \pm 1.4)\,\%$	
Γ_{86}	$K^*(892)^- \pi^+ \pi^+$ total			
Γ_{87}	$K^*(892)^- \pi^+ \pi^+$ 3-body		$(2.0 \pm 0.9)\,\%$	
Γ_{88}	$K^- \rho^+ \pi^+$ total		$(3.1 \pm 1.1)\,\%$	
Γ_{89}	$K^- \rho^+ \pi^+$ 3-body		$(1.1 \pm 0.4)\,\%$	
Γ_{90}	$\overline{K}^0 \rho^0 \pi^+$ total		$(4.2 \pm 0.9)\,\%$	CL=90%
Γ_{91}	$\overline{K}^0 \rho^0 \pi^+$ 3-body		$(5 \pm 5) \times 10^{-3}$	
Γ_{92}	$\overline{K}^0 f_0(980) \pi^+$		$< 5 \times 10^{-3}$	CL=90%
Γ_{93}	$\overline{K}^*(892)^0 \pi^+ \pi^+ \pi^-$		$(8.1 \pm 3.4) \times 10^{-3}$	S=1.7
Γ_{94}	$\overline{K}^*(892)^0 \rho^0 \pi^+$		$(2.9^{+1.7}_{-1.5}) \times 10^{-3}$	S=1.8
Γ_{95}	$\overline{K}^*(892)^0 \pi^+ \pi^+ \pi^-$ no-ρ		$(4.3 \pm 1.7) \times 10^{-3}$	
Γ_{96}	$K^- \rho^0 \pi^+ \pi^+$		$(3.1 \pm 0.9) \times 10^{-3}$	

Pionic modes

Γ_{97}	$\pi^+ \pi^0$		$(2.5 \pm 0.7) \times 10^{-3}$	
Γ_{98}	$\pi^+ \pi^+ \pi^-$		$(3.6 \pm 0.4) \times 10^{-3}$	
Γ_{99}	$\rho^0 \pi^+$		$(1.05 \pm 0.31) \times 10^{-3}$	
Γ_{100}	$\pi^+ \pi^+ \pi^-$ nonresonant		$(2.2 \pm 0.4) \times 10^{-3}$	
Γ_{101}	$\pi^+ \pi^+ \pi^- \pi^0$		$(1.9^{+1.5}_{-1.2})\,\%$	
Γ_{102}	$\eta \pi^+$ $\times$ B($\eta \to \pi^+ \pi^- \pi^0$)		$(1.7 \pm 0.6) \times 10^{-3}$	
Γ_{103}	$\omega \pi^+$ $\times$ B($\omega \to \pi^+ \pi^- \pi^0$)		$< 6 \times 10^{-3}$	CL=90%
Γ_{104}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^-$		$(2.1 \pm 0.4) \times 10^{-3}$	
Γ_{105}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0$		$(2.9^{+2.9}_{-2.0}) \times 10^{-3}$	

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{106}	$\eta \pi^+$		$(7.5 \pm 2.5) \times 10^{-3}$	
Γ_{107}	$\rho^0 \pi^+$		$(1.05 \pm 0.31) \times 10^{-3}$	
Γ_{108}	$\omega \pi^+$		$< 7 \times 10^{-3}$	CL=90%
Γ_{109}	$\eta \rho^+$		$< 1.2\,\%$	CL=90%
Γ_{110}	$\eta'(958) \pi^+$		$< 9 \times 10^{-3}$	CL=90%
Γ_{111}	$\eta'(958) \rho^+$		$< 1.5\,\%$	CL=90%

Hadronic modes with a $K\overline{K}$ pair

Γ_{112}	$K^+ \overline{K}^0$		$(7.4 \pm 1.0) \times 10^{-3}$	
Γ_{113}	$K^+ K^- \pi^+$	[d]	$(8.8 \pm 0.8) \times 10^{-3}$	
Γ_{114}	$\phi \pi^+$ $\times$ B($\phi \to K^+ K^-$)		$(3.0 \pm 0.3) \times 10^{-3}$	
Γ_{115}	$K^+ \overline{K}^*(892)^0$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)		$(2.8 \pm 0.4) \times 10^{-3}$	
Γ_{116}	$K^+ K^- \pi^+$ nonresonant		$(4.5 \pm 0.9) \times 10^{-3}$	
Γ_{117}	$K^0 \overline{K}^0 \pi^+$		—	
Γ_{118}	$K^*(892)^+ \overline{K}^0$ $\times$ B($K^{*+} \to K^0 \pi^+$)		$(2.1 \pm 1.0)\,\%$	
Γ_{119}	$K^+ K^- \pi^+ \pi^0$		—	
Γ_{120}	$\phi \pi^+ \pi^0$ $\times$ B($\phi \to K^+ K^-$)		$(1.1 \pm 0.5)\,\%$	

Γ_{121}	$\phi\rho^+ \times B(\phi \to K^+K^-)$		< 7	$\times 10^{-3}$	CL=90%
Γ_{122}	$K^+K^-\pi^+\pi^0$ non-ϕ		$(1.5^{+0.7}_{-0.6})$ %		
Γ_{123}	$K^+\overline{K}^0\pi^+\pi^-$		< 2	%	CL=90%
Γ_{124}	$K^0K^-\pi^+\pi^+$		(1.0 ± 0.6) %		
Γ_{125}	$K^*(892)^+\overline{K}^*(892)^0 \times B^2(K^{*+} \to K^0\pi^+)$		(1.2 ± 0.5) %		
Γ_{126}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 7.9	$\times 10^{-3}$	CL=90%
Γ_{127}	$K^+K^-\pi^+\pi^+\pi^-$		—		
Γ_{128}	$\phi\pi^+\pi^+\pi^- \times B(\phi \to K^+K^-)$		< 1	$\times 10^{-3}$	CL=90%
Γ_{129}	$K^+K^-\pi^+\pi^+\pi^-$ nonresonant		< 3	%	CL=90%

Fractions of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{130}	$\phi\pi^+$		$(6.1 \pm 0.6) \times 10^{-3}$		
Γ_{131}	$\phi\pi^+\pi^0$		(2.3 ± 1.0) %		
Γ_{132}	$\phi\rho^+$		< 1.4	%	CL=90%
Γ_{133}	$\phi\pi^+\pi^+\pi^-$		< 2	$\times 10^{-3}$	CL=90%
Γ_{134}	$K^+\overline{K}^*(892)^0$		$(4.2 \pm 0.5) \times 10^{-3}$		
Γ_{135}	$K^*(892)^+\overline{K}^0$		(3.2 ± 1.5) %		
Γ_{136}	$K^*(892)^+\overline{K}^*(892)^0$		(2.6 ± 1.1) %		

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) or Lepton number (*L*) violating modes

Γ_{137}	$K^+\pi^+\pi^-$	*DC*	$(6.8 \pm 1.5) \times 10^{-4}$		
Γ_{138}	$K^+\rho^0$	*DC*	$(2.5 \pm 1.2) \times 10^{-4}$		
Γ_{139}	$K^*(892)^0\pi^+$	*DC*	$(3.6 \pm 1.6) \times 10^{-4}$		
Γ_{140}	$K^+\pi^+\pi^-$ nonresonant	*DC*	$(2.4 \pm 1.2) \times 10^{-4}$		
Γ_{141}	$K^+K^+K^-$	*DC*	< 1.4	$\times 10^{-4}$	CL=90%
Γ_{142}	ϕK^+	*DC*	< 1.3	$\times 10^{-4}$	CL=90%
Γ_{143}	$\pi^+e^+e^-$	*C1*	< 6.6	$\times 10^{-5}$	CL=90%
Γ_{144}	$\pi^+\mu^+\mu^-$	*C1*	< 1.8	$\times 10^{-5}$	CL=90%
Γ_{145}	$\rho^+\mu^+\mu^-$	*C1*	< 5.6	$\times 10^{-4}$	CL=90%
Γ_{146}	$K^+e^+e^-$	[*f*]	< 2.0	$\times 10^{-4}$	CL=90%
Γ_{147}	$K^+\mu^+\mu^-$	[*f*]	< 9.7	$\times 10^{-5}$	CL=90%
Γ_{148}	$\pi^+e^+\mu^-$	*LF*	< 1.1	$\times 10^{-4}$	CL=90%
Γ_{149}	$\pi^+e^-\mu^+$	*LF*	< 1.3	$\times 10^{-4}$	CL=90%
Γ_{150}	$K^+e^+\mu^-$	*LF*	< 1.3	$\times 10^{-4}$	CL=90%
Γ_{151}	$K^+e^-\mu^+$	*LF*	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{152}	$\pi^-e^+e^+$	*L*	< 1.1	$\times 10^{-4}$	CL=90%
Γ_{153}	$\pi^-\mu^+\mu^+$	*L*	< 8.7	$\times 10^{-5}$	CL=90%
Γ_{154}	$\pi^-e^+\mu^+$	*L*	< 1.1	$\times 10^{-4}$	CL=90%
Γ_{155}	$\rho^-\mu^+\mu^+$	*L*	< 5.6	$\times 10^{-4}$	CL=90%
Γ_{156}	$K^-e^+e^+$	*L*	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{157}	$K^-\mu^+\mu^+$	*L*	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{158}	$K^-e^+\mu^+$	*L*	< 1.3	$\times 10^{-4}$	CL=90%
Γ_{159}	$K^*(892)^-\mu^+\mu^+$	*L*	< 8.5	$\times 10^{-4}$	CL=90%

Γ_{160}	A dummy mode used by the fit.		(33 ± 5) %		

[*a*] This is a weighted average of $D^{\pm}$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \to$ (η anything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in these Particle Listings.

[*b*] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ here is really an e^+.

[*c*] An ℓ indicates an e or a μ mode, not a sum over these modes.

[*d*] The branching fraction for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[*e*] The two experiments measuring this fraction are in serious disagreement. See the Particle Listings.

[*f*] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

CONSTRAINED FIT INFORMATION

An overall fit to 32 branching ratios uses 54 measurements and one constraint to determine 20 parameters. The overall fit has a $\chi^2 = 20.8$ for 35 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_{11}	5									
x_{16}	4	2								
x_{25}	18	29	8							
x_{26}	14	7	31	25						
x_{33}	38	9	8	31	25					
x_{34}	32	16	14	56	45	55				
x_{39}	0	0	0	0	0	0	0			
x_{43}	7	4	3	13	10	12	23	0		
x_{52}	9	5	4	17	14	16	30	0	18	
x_{59}	15	8	7	28	22	27	49	0	11	15
x_{73}	21	11	9	37	29	36	65	0	15	20
x_{80}	5	3	2	9	7	8	16	0	31	37
x_{87}	3	1	1	5	4	5	9	0	29	13
x_{93}	5	2	2	9	7	8	15	0	3	5
x_{94}	3	2	1	6	5	6	11	0	2	3
x_{98}	19	10	9	35	28	33	61	0	14	18
x_{100}	11	5	5	19	15	18	34	0	8	10
x_{112}	22	7	6	23	18	53	41	0	9	12
x_{160}	−35	−26	−12	−41	−34	−38	−55	−58	−46	−45
	x_9	x_{11}	x_{16}	x_{25}	x_{26}	x_{33}	x_{34}	x_{39}	x_{43}	x_{52}

x_{73}	32								
x_{80}	8	10							
x_{87}	4	6	12						
x_{93}	29	10	2	1					
x_{94}	8	7	2	1	15				
x_{98}	30	40	10	5	9	7			
x_{100}	16	22	5	3	5	4	43		
x_{112}	20	26	6	4	6	4	25	14	
x_{160}	−30	−38	−46	−32	−16	−10	−35	−19	−27
	x_{59}	x_{73}	x_{80}	x_{87}	x_{93}	x_{94}	x_{98}	x_{100}	x_{112}

D^+ BRANCHING RATIOS

See the "Note on *D* Mesons" above. Some now-obsolete measurements have been omitted from these Listings.

——— Inclusive modes ———

$\Gamma(e^+\text{anything})/\Gamma_{total}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.172±0.019 OUR AVERAGE					
$0.20^{+0.09}_{-0.07}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.170±0.019±0.007	158	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
0.168±0.064	23	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.220^{+0.044}_{-0.022}$		BACINO	80	DLCO	e^+e^- 3.77 GeV

D^+ and $D^0 \to$ (e^+anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only experiments at E_{cm} = 3.77 GeV are included in the average here. We don't put this result in the Meson Summary Table.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.110±0.011 OUR AVERAGE	Error includes scale factor of 1.1.				
0.117±0.011	295	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
0.10 ±0.032		[4] SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.072±0.028		FELLER	78	MRK1	e^+e^- 3.772 GeV

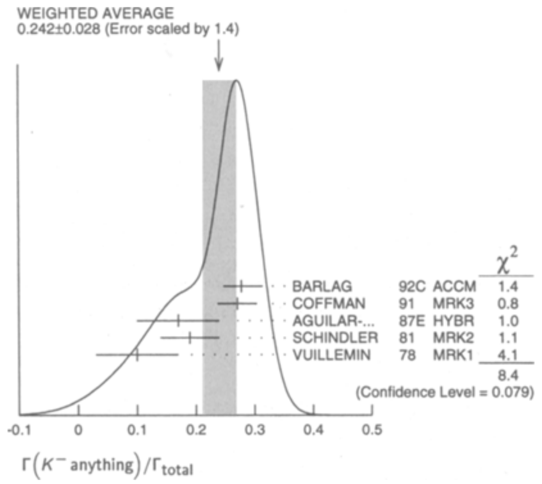
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.096 \pm 0.004 \pm 0.011$	2207	[5] ALBRECHT 96C	ARG	$e^+e^- \approx$ 10 GeV
$0.134 \pm 0.015 \pm 0.010$		[6] ABE 93E	VNS	e^+e^- 58 GeV
$0.098 \pm 0.009 ^{+0.006}_{-0.005}$	240	[7] ALBRECHT 92F	ARG	$e^+e^- \approx$ 10 GeV
$0.096 \pm 0.007 \pm 0.015$		[8] ONG 88	MRK2	e^+e^- 29 GeV
$0.116 ^{+0.011}_{-0.009}$		[8] PAL 86	DLCO	e^+e^- 29 GeV
$0.091 \pm 0.009 \pm 0.013$		[8] AIHARA 85	TPC	e^+e^- 29 GeV
$0.092 \pm 0.022 \pm 0.040$		[8] ALTHOFF 84J	TASS	e^+e^- 34.6 GeV
0.091 ± 0.013		[8] KOOP 84	DLCO	See PAL 86
0.08 ± 0.015		[9] BACINO 79	DLCO	e^+e^- 3.772 GeV

[4] Isolates D^+ and $D^0 \to e^+ X$ and weights for relative production (44%–56%).
[5] ALBRECHT 96C uses e^- in the hemisphere opposite to $D^{*+} \to D^0\pi^+$ events.
[6] ABE 93E also measures forward-backward asymmetries and fragmentation functions for c and b quarks.
[7] ALBRECHT 92F uses the excess of right-sign over wrong-sign leptons in a sample of events tagged by fully reconstructed $D^*(2010)^+ \to D^0\pi^+$ decays.
[8] Average BR for charm $\to e^+ X$. Unlike at E_{cm} = 3.77 GeV, the admixture of charmed mesons is unknown.
[9] Not independent of BACINO 80 measurements of $\Gamma(e^+\text{anything})/\Gamma_{total}$ for the D^+ and D^0 separately.

$\Gamma(K^-\text{anything})/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.242 ± 0.028 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
$0.278 ^{+0.036}_{-0.031}$		[10] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.271 \pm 0.023 \pm 0.024$		COFFMAN 91	MRK3	e^+e^- 3.77 GeV
0.17 ± 0.07		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.19 ± 0.05	26	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.10 ± 0.07	3	VUILLEMIN 78	MRK1	e^+e^- 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.16 ^{+0.08}_{-0.07}$		AGUILAR-... 86B	HYBR	See AGUILAR-BENITEZ 87E

[10] BARLAG 92C computes the branching fraction using topological normalization.



$\left[\Gamma(\overline{K}^0\text{anything}) + \Gamma(K^0\text{anything})\right]/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.59 ± 0.07 OUR AVERAGE				
$0.612 \pm 0.065 \pm 0.043$		COFFMAN 91	MRK3	e^+e^- 3.77 GeV
0.52 ± 0.18	15	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.39 ± 0.29	3	VUILLEMIN 78	MRK1	e^+e^- 3.772 GeV

$\Gamma(K^+\text{anything})/\Gamma_{total}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.058 ± 0.014 OUR AVERAGE				
$0.055 \pm 0.013 \pm 0.009$		COFFMAN 91	MRK3	e^+e^- 3.77 GeV
$0.08 ^{+0.06}_{-0.05}$		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.06 ± 0.04	12	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.06 ± 0.06	2	VUILLEMIN 78	MRK1	e^+e^- 3.772 GeV

D^+ and $D^0 \to (\eta\ \text{anything})$ / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only the experiment at E_{cm} = 3.77 GeV is used.

VALUE	DOCUMENT ID	TECN	COMMENT
<0.13	PARTRIDGE 81	CBAL	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.02	[11] BRANDELIK 79	DASP	e^+e^- 4.03 GeV

[11] The BRANDELIK 79 result is based on the absence of an η signal at E_{cm} = 4.03 GeV. PARTRIDGE 81 observes a substantially higher η cross section at 4.03 GeV.

$\Gamma(c/\overline{c} \to \mu^+\text{anything})/\Gamma(c/\overline{c} \to \text{anything})$

This is the average branching ratio for charm $\to \mu^+ X$. The mixture of charmed particles is unknown and may actually contain states other than D mesons. We don't put this result in the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.081 ^{+0.010}_{-0.009}$ OUR AVERAGE				
$0.086 \pm 0.017 ^{+0.008}_{-0.007}$	69	[12] ALBRECHT 92F	ARG	$e^+e^- \approx$ 10 GeV
$0.078 \pm 0.009 \pm 0.012$		ONG 88	MRK2	e^+e^- 29 GeV
$0.078 \pm 0.015 \pm 0.02$		BARTEL 87	JADE	e^+e^- 34.6 GeV
$0.082 \pm 0.012 ^{+0.02}_{-0.01}$		ALTHOFF 84G	TASS	e^+e^- 34.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.089 \pm 0.018 \pm 0.025$		BARTEL 85J	JADE	See BARTEL 87

[12] ALBRECHT 92F uses the excess of right-sign over wrong-sign leptons in a sample of events tagged by fully reconstructed $D^*(2010)^+ \to D^0\pi^+$ decays.

—— Leptonic and semileptonic modes ——

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_7/Γ

See the "Note on Pseudoscalar-Meson Decay Constants" in the $\pi^{\pm}$ Listings for the limit inferred on the D^+ decay constant from the limit here on $\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.00072	90		ADLER 88B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	90	0	[13] AUBERT 83	SPEC	μ^+ Fe, 250 GeV

[13] AUBERT 83 obtains an upper limit 0.014 assuming the final state contains equal amounts of (D^+,D^-), $(D^+,\overline{D}^0)$, (D^-,D^0), and $(D^0,\overline{D}^0)$. We quote the limit they get under more general assumptions.

$\Gamma(\overline{K}^0\ell^+\nu_\ell)/\Gamma_{total}$ — Γ_8/Γ

We average our $\overline{K}^0 e^+\nu_e$ and $\overline{K}^0\mu^+\nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.03 to be able to use it with the $\overline{K}^0 e^+\nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID	COMMENT
0.068 ± 0.008 OUR AVERAGE		
0.067 ± 0.009	PDG 98	Our $\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma_{total}$
$0.072 ^{+0.031}_{-0.020}$	PDG 98	1.03 × our $\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma_{total}$

$\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.067 ± 0.009 OUR FIT				
$0.06 ^{+0.022}_{-0.013} \pm 0.007$	13	BAI 91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma(\overline{K}^0\pi^+)$ — Γ_9/Γ_{33}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.32 ± 0.31 OUR FIT				
$2.60 \pm 0.35 \pm 0.26$	186	[14] BEAN 93C	CLE2	$e^+e^- \approx \Upsilon(4S)$

[14] BEAN 93C uses $\overline{K}^0\mu^+\nu_\mu$ as well as $\overline{K}^0 e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(\overline{K}^0 e^+\nu_e)/\Gamma(K^-\pi^+\pi^+)$ — Γ_9/Γ_{34}

VALUE	DOCUMENT ID	TECN	COMMENT
0.74 ± 0.10 OUR FIT			
$0.66 \pm 0.09 \pm 0.14$	ANJOS 91C	E691	γ Be 80–240 GeV

$\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.07 ^{+0.028}_{-0.016} \pm 0.012$	14	BAI 91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma(\mu^+\text{anything})$ — Γ_{10}/Γ_6

VALUE	EVTS	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.76 ± 0.06	84	[15] AOKI 88	π^- emulsion

[15] From topological branching ratios in emulsion with an identified muon.

$\Gamma(K^-\pi^+e^+\nu_e)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$0.041 ^{+0.009}_{-0.007}$ OUR FIT					
$0.035 ^{+0.012}_{-0.007} \pm 0.004$		14	[16] BAI 91	MRK3	$e^+e^- \approx$ 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.057	90		[17] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[16] BAI 91 finds that a fraction $0.79 ^{+0.15}_{-0.17} {}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892)e^+\nu_e$.
[17] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^{*}(892)^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ Γ_{24}/Γ

We average our $\overline{K}^{*0} e^+ \nu_e$ and $\overline{K}^{*0} \mu^+ \nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.05 to be able to use it with the $\overline{K}^{*0} e^+ \nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID		COMMENT
0.047±0.004 OUR AVERAGE			
0.048±0.005	PDG	98	Our $\Gamma(\overline{K}^{*0} e^+ \nu_e)/\Gamma_{\text{total}}$
0.046±0.006	PDG	98	1.05 × our $\Gamma(\overline{K}^{*0} \mu^+ \nu_\mu)/\Gamma_{\text{total}}$

$\Gamma(\overline{K}^{*}(892)^0 e^+ \nu_e)/\Gamma(K^- \pi^+ e^+ \nu_e)$ Γ_{25}/Γ_{11}

Unseen decay modes of the $\overline{K}^{*}(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.16^{+0.21}_{-0.24}$ OUR FIT					
1.0 ±0.3	35	ADAMOVICH	91	OMEG	π^- 340 GeV

$\Gamma(\overline{K}^{*}(892)^0 e^+ \nu_e)/\Gamma(K^- \pi^+ \pi^+)$ Γ_{25}/Γ_{34}

Unseen decay modes of the $\overline{K}^{*}(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.53±0.05 OUR FIT					
0.54±0.05 OUR AVERAGE					
0.67±0.09±0.07	710	[18] BEAN	93C	CLE2	$e^+ e^- \approx \Upsilon(4S)$
0.62±0.15±0.09	35	ADAMOVICH	91	OMEG	π^- 340 GeV
0.55±0.08±0.10	880	ALBRECHT	91	ARG	$e^+ e^- \approx$ 10.4 GeV
0.49±0.04±0.05		ANJOS	89B	E691	Photoproduction

[18] BEAN 93C uses $\overline{K}^{*0} \mu^+ \nu_\mu$ as well as $\overline{K}^{*0} e^+ \nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(K^- \pi^+ e^+ \nu_e \text{ nonresonant})/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	[19] ANJOS	89B	E691	Photoproduction

[19] ANJOS 89B assumes a $\Gamma(D^+ \rightarrow K^- \pi^+ \pi^+)/\Gamma_{\text{total}} = 9.1 \pm 1.3 \pm 0.4\%$.

$\Gamma(K^- \pi^+ \mu^+ \nu_\mu)/\Gamma_{\text{total}}$ $\Gamma_{14}/\Gamma = (\Gamma_{16}+\frac{2}{3}\Gamma_{26})/\Gamma$

VALUE	DOCUMENT ID
0.032±0.004 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\overline{K}^{*}(892)^0 \mu^+ \nu_\mu)/\Gamma_{\text{total}}$ Γ_{26}/Γ

Unseen decay modes of the $\overline{K}^{*}(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.044 ±0.006 OUR FIT	Error includes scale factor of 1.1.				
0.0325±0.0071±0.0075	224	[20] KODAMA	92C	E653	π^- emulsion 600 GeV

[20] KODAMA 92C measures $\Gamma(D^+ \rightarrow \overline{K}^{*0} \mu^+ \nu_\mu)/\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu) = 0.43 \pm 0.09 \pm 0.09$ and then uses $\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu) = (7.0 \pm 0.7) \times 10^{10}\,\text{s}^{-1}$ to get the quoted branching fraction. See also the footnote to KODAMA 92C in the next data block.

$\Gamma(\overline{K}^{*}(892)^0 \mu^+ \nu_\mu)/\Gamma(K^- \pi^+ \pi^+)$ Γ_{26}/Γ_{34}

Unseen decay modes of the $\overline{K}^{*}(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.06 OUR FIT					
0.53±0.06 OUR AVERAGE					
0.56±0.04±0.06	875	FRABETTI	93E	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV
0.46±0.07±0.08	224	[21] KODAMA	92C	E653	π^- emulsion 600 GeV

[21] KODAMA 92C uses the same $\overline{K}^{*0} \mu^+ \nu_\mu$ events normalizing instead with $D^0 \rightarrow K^- \mu^+ \nu_\mu$ events, as reported in the preceding data block.

$\Gamma(K^- \pi^+ \mu^+ \nu_\mu \text{ nonresonant})/\Gamma(K^- \pi^+ \mu^+ \nu_\mu)$ $\Gamma_{16}/\Gamma_{14} = \Gamma_{16}/(\Gamma_{16}+\frac{2}{3}\Gamma_{26})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.083±0.029 OUR FIT				
0.083±0.029	FRABETTI	93E	E687	< 0.12 (90% CL)

$\Gamma(\overline{K}^0 \pi^+ \pi^- e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[22] AGUILAR-...	87F	HYBR	πp, $p p$ 360, 400 GeV

[22] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(K^- \pi^+ \pi^0 e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[23] AGUILAR-...	87F	HYBR	πp, $p p$ 360, 400 GeV

[23] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma((\overline{K}^{*}(892)\pi)^0 e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{19}/Γ

Unseen decay modes of the $\overline{K}^{*}(892)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	ANJOS	92	E691	Photoproduction

$\Gamma((\overline{K}\pi\pi)^0 e^+ \nu_e \text{ non-}\overline{K}^{*}(892))/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	ANJOS	92	E691	Photoproduction

$\Gamma(K^- \pi^+ \pi^0 \mu^+ \nu_\mu)/\Gamma(K^- \pi^+ \mu^+ \nu_\mu)$ $\Gamma_{21}/\Gamma_{14} = \Gamma_{21}/(\Gamma_{16}+\frac{2}{3}\Gamma_{26})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.042	90	FRABETTI	93E	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\pi^0 \ell^+ \nu_\ell)/\Gamma(\overline{K}^0 \ell^+ \nu_\ell)$ Γ_{22}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.046±0.014±0.017	100	[24] BARTELT	97	CLE2	$e^+ e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.085±0.027±0.014	53	[25] ALAM	93	CLE2	See BARTELT 97

[24] BARTELT 97 thus directly measures the product of ratios squared of CKM matrix elements and form factors at q^2=0: $|V_{cd}/V_{cs}|^2 \cdot |f_+^{\pi}(0)/f_+^{K}(0)|^2 = 0.046 \pm 0.014 \pm 0.017$.

[25] ALAM 93 thus directly measures the product of ratios squared of CKM matrix elements and form factors at q^2=0: $|V_{cd}/V_{cs}|^2 \cdot |f_+^{\pi}(0)/f_+^{K}(0)|^2 = 0.085 \pm 0.027 \pm 0.014$.

$\Gamma(\pi^+ \pi^- e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.057	90	[26] AGUILAR-...	87F	HYBR	πp, $p p$ 360, 400 GeV

[26] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\rho^0 e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0037	90	BAI	91	MRK3	$e^+ e^- \approx$ 3.77 GeV

$\Gamma(\rho^0 e^+ \nu_e)/\Gamma(\overline{K}^{*}(892)^0 e^+ \nu_e)$ Γ_{27}/Γ_{25}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.045±0.014±0.009	49	[27] AITALA	97	E791	π^- nucleus, 500 GeV

[27] AITALA 97 explicitly subtracts $D^+ \rightarrow \eta' e^+ \nu_e$ and other backgrounds to get this result.

$\Gamma(\rho^0 \mu^+ \nu_\mu)/\Gamma(\overline{K}^{*}(892)^0 \mu^+ \nu_\mu)$ Γ_{28}/Γ_{26}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.061±0.014 OUR AVERAGE					
0.051±0.015±0.009	54	[28] AITALA	97	E791	π^- nucleus, 500 GeV
0.079±0.019±0.013	39	[29] FRABETTI	97	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.044^{+0.031}_{-0.025}\pm0.014$	4	[30] KODAMA	93C	E653	π^- emulsion 600 GeV

[28] AITALA 97 explicitly subtracts $D^+ \rightarrow \eta' \mu^+ \nu_\mu$ and other backgrounds to get this result.

[29] Because the reconstruction efficiency for photons is low, this FRABETTI 97 result also includes any $D^+ \rightarrow \eta' \mu^+ \nu_\mu \rightarrow \gamma \rho^0 \mu^+ \nu_\mu$ events in the numerator.

[30] This KODAMA 93C result is based on a final signal of $4.0^{+2.8}_{-2.3} \pm 1.3$ events; the estimates of backgrounds that affect this number are somewhat model dependent.

$\Gamma(\phi e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{29}/Γ

Decay modes of the ϕ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0209	90	BAI	91	MRK3	$e^+ e^- \approx$ 3.77 GeV

$\Gamma(\phi \mu^+ \nu_\mu)/\Gamma_{\text{total}}$ Γ_{30}/Γ

Decay modes of the ϕ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0372	90	BAI	91	MRK3	$e^+ e^- \approx$ 3.77 GeV

$\Gamma(\eta \ell^+ \nu_\ell)/\Gamma(\pi^0 \ell^+ \nu_\ell)$ Γ_{31}/Γ_{22}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	BARTELT	97	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\eta'(958) \mu^+ \nu_\mu)/\Gamma(\overline{K}^{*}(892)^0 \mu^+ \nu_\mu)$ Γ_{32}/Γ_{26}

Decay modes of the $\eta'(958)$ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.20	90	KODAMA	93B	E653	π^- emulsion 600 GeV

Hadronic modes with a $\overline{K}$ or $\overline{K} K \overline{K}$

$\Gamma(\overline{K}^0 \pi^+)/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0289±0.0026 OUR FIT	Error includes scale factor of 1.1.				
0.032 ±0.004 OUR AVERAGE					
0.032 ±0.005 ±0.002	161	ADLER	88C	MRK3	$e^+ e^-$ 3.77 GeV
0.033 ±0.009	36	[31] SCHINDLER	81	MRK2	$e^+ e^-$ 3.771 GeV
0.033 ±0.013	17	[32] PERUZZI	77	MRK1	$e^+ e^-$ 3.77 GeV

[31] SCHINDLER 81 (MARK-2) measures $\sigma(e^+ e^- \rightarrow \psi(3770))$ × branching fraction to be 0.14 ± 0.03 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[32] PERUZZI 77 (MARK-1) measures $\sigma(e^+ e^- \rightarrow \psi(3770))$ × branching fraction to be 0.14 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

$\Gamma(\overline{K}^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{33}/Γ_{34}

It is generally assumed for modes such as $D^+ \rightarrow \overline{K}^0\pi^+$ that

$$\Gamma(D^+ \rightarrow \overline{K}^0\pi^+) = 2\Gamma(D^+ \rightarrow K^0_S\pi^+);$$

it is the latter Γ that is actually measured. BIGI 95 points out that interference between Cabibbo-allowed and doubly Cabibbo-suppressed amplitudes, where both occur, could invalidate this assumption by a few percent.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.321±0.025 OUR FIT Error includes scale factor of 1.1.				
0.32 ±0.04 OUR AVERAGE Error includes scale factor of 1.4.				
0.348±0.024±0.022	473	[33] BISHAI 97	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.274±0.030±0.031	264	ANJOS 90C	E691	Photoproduction

[33] See BISHAI 97 for an isospin analysis of $D^+ \rightarrow \overline{K}\pi$ amplitudes.

$\Gamma(K^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.090±0.006 OUR FIT				
0.091±0.007 OUR AVERAGE				
0.093±0.006±0.008	1502	[34] BALEST 94	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.091±0.013±0.004	1164	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.091±0.019	239	[35] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.086±0.020	85	[36] PERUZZI 77	MRK1	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.064^{+0.015}_{-0.014}$		[37] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.063^{+0.028}_{-0.014}\pm0.011$	8	[37] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[34] BALEST 94 measures the ratio of $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+$ branching fractions to be 2.35 ± 0.16 ± 0.16 and uses their absolute measurement of the $D^0 \rightarrow K^-\pi^+$ fraction (AKERIB 93).

[35] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \rightarrow \psi(3770))$ × branching fraction to be 0.38 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[36] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \rightarrow \psi(3770))$ × branching fraction to be 0.36 ± 0.06 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[37] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^*(892)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{73}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.212±0.016 OUR FIT				
0.210±0.015 OUR AVERAGE				
0.206±0.009±0.014		FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.255±0.014±0.050		ANJOS 93	E691	γBe 90–260 GeV
0.21 ±0.06 ±0.06		ALVAREZ 91B	NA14	Photoproduction
0.20 ±0.02 ±0.11		ADLER 87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.053	90	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(\overline{K}^*_0(1430)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{82}/Γ_{34}

Unseen decay modes of the $\overline{K}^*_0(1430)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.41 ±0.04 OUR AVERAGE			
0.458±0.035±0.094	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.400±0.031±0.027	ANJOS 93	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(1680)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{83}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(1680)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.160±0.032 OUR AVERAGE Error includes scale factor of 1.1.			
0.182±0.023±0.028	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.113±0.015±0.050	ANJOS 93	E691	γBe 90–260 GeV

$\Gamma(K^-\pi^+\pi^+ \text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ Γ_{38}/Γ_{34}

VALUE	DOCUMENT ID	TECN	COMMENT
0.96 ±0.07 OUR AVERAGE			
0.998±0.037±0.072	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.838±0.088±0.275	ANJOS 93	E691	γBe 90–260 GeV
0.79 ±0.07 ±0.15	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.097±0.030 OUR FIT Error includes scale factor of 1.1.				
0.107±0.029 OUR AVERAGE				
0.102±0.025±0.016	159	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.19 ±0.12	10	[38] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

[38] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \rightarrow \psi(3770))$ × branching fraction to be 0.78 ± 0.48 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

$\Gamma(\overline{K}^0\rho^+)/\Gamma(\overline{K}^0\pi^+\pi^0)$ Γ_{40}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.68±0.08±0.12	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^0)$ Γ_{73}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.20±0.06 OUR FIT			
0.57±0.18±0.18	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^0 \text{ nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^0)$ Γ_{42}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.13±0.07±0.08	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_{43}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.064±0.011 OUR FIT				
0.058±0.012±0.012	142	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.034^{+0.056}_{-0.070}$		[39] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[39] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV
$0.063^{+0.014}_{-0.013}\pm0.012$	175	BALTRUSAIT...86E	MRK3	See COFFMAN 92B

[39] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{43}/Γ_{34}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.71±0.12 OUR FIT				
0.76±0.11±0.12	91	ANJOS 92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.69±0.10±0.16		ANJOS 89E	E691	See ANJOS 92C
$0.57^{+0.65}_{-0.17}$	1	AGUILAR-... 83B	HYBR	$\pi^- p$, 360 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+ \text{ total})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{74}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.33±0.165±0.12	[40] ANJOS 92C	E691	γBe 90–260 GeV

[40] See, however, the next entry, where the two experiments disagree completely.

$\Gamma(\overline{K}^*(892)^0\rho^+ \text{ S-wave})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{75}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included. The two experiments here disagree completely.

VALUE	DOCUMENT ID	TECN	COMMENT
0.26 ±0.25 OUR AVERAGE Error includes scale factor of 3.1.			
0.15 ±0.075±0.045	ANJOS 92C	E691	γBe 90–260 GeV
0.833±0.116±0.165	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+ \text{ P-wave})/\Gamma_{\text{total}}$ Γ_{76}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.001	90	ANJOS 92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.005	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+ \text{ D-wave})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{77}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.15±0.09±0.045	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+ \text{ D-wave longitudinal})/\Gamma_{\text{total}}$ Γ_{78}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{80}/Γ_{43}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.77 ±0.20 OUR FIT			
0.907±0.218±0.180	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\rho^+\pi^+ \text{ total})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{88}/Γ_{43}

This includes $\overline{K}^*(892)^0\rho^+$, *etc.* The next entry gives the specifically 3-body fraction.

VALUE	DOCUMENT ID	TECN	COMMENT
0.48±0.13±0.09	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(K^-\rho^+\pi^+ \text{ 3-body})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{89}/Γ_{43}

VALUE	DOCUMENT ID	TECN	COMMENT
0.17 ±0.06 OUR AVERAGE			
0.18 ±0.08 ±0.04	ANJOS 92C	E691	γBe 90–260 GeV
0.159±0.065±0.060	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0 \text{ total})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{84}/Γ_{43}

This includes $\overline{K}^*(892)^0\rho^+$, *etc.* The next two entries give the specifically 3-body fraction. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
1.05±0.11±0.08	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0\ \text{3-body})/\Gamma_{\text{total}}$ Γ_{85}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.008	90	[41] COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

[41] See, however, the next entry: ANJOS 92C sees a large signal in this channel.

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{85}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.66±0.09±0.17	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{87}/Γ_{43}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.32±0.14 OUR FIT Error includes scale factor of 1.1.			
0.24±0.12±0.09	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0\ \text{nonresonant})/\Gamma_{\text{total}}$ Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.002	90	[42] ANJOS 92C	E691	γBe 90–260 GeV

[42] Whereas ANJOS 92C finds no signal here, COFFMAN 92B finds a fairly large one; see the next entry.

$\Gamma(K^-\pi^+\pi^+\pi^0\ \text{nonresonant})/\Gamma(K^-\pi^+\pi^+\pi^0)$ Γ_{51}/Γ_{43}

VALUE	DOCUMENT ID	TECN	COMMENT
0.184±0.070±0.050	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{52}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.070±0.009 OUR FIT				
0.071±0.016 OUR AVERAGE				
0.066±0.015±0.005	168	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.12 ±0.05	21	[43] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.042^{+0.019}_{-0.017}$		[44] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.243^{+0.064}_{-0.041}\pm0.041$	11	[44] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[43] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770))$ × branching fraction to be 0.51 ± 0.08 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[44] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{52}/Γ_{34}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78±0.10 OUR FIT				
0.77±0.07±0.11	229	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^0 a_1(1260)^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{71}/Γ_{52}

Unseen decay modes of the $a_1(1260)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
1.15 ±0.19 OUR AVERAGE Error includes scale factor of 1.1.			
1.66 ±0.28 ±0.40	ANJOS 92C	E691	γBe 90–260 GeV
1.078±0.114±0.140	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_2(1320)^+)/\Gamma_{\text{total}}$ Γ_{72}/Γ

Unseen decay modes of the $a_2(1320)^+$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.003	90	ANJOS 92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.008	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1270)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{79}/Γ

Unseen decay modes of the $\overline{K}_1(1270)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	ANJOS 92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.011	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{80}/Γ

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.009	90	[45] ANJOS 92C	E691	γBe 90–260 GeV

[45] ANJOS 92C sees no evidence for $\overline{K}_1(1400)^0\pi^+$ in either the $\overline{K}^0\pi^+\pi^+\pi^-$ or $K^-\pi^+\pi^+\pi^0$ channels, whereas COFFMAN 92B finds the $\overline{K}_1(1400)^0\pi^+$ branching fraction to be large; see the next entry.

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{80}/Γ_{52}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.70 ±0.17 OUR FIT			
0.623±0.106±0.180	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(1410)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{81}/Γ

Unseen decay modes of the $\overline{K}^*(1410)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+\ \text{total})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{86}/Γ_{52}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41±0.14	14	ALEEV 94	BIS2	nN 20–70 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+\ \text{3-body})/\Gamma_{\text{total}}$ Γ_{87}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.020±0.009 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.013	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+\ \text{3-body})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{87}/Γ_{52}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.29±0.13 OUR FIT Error includes scale factor of 1.1.			
0.50±0.09±0.21	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+\ \text{total})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{90}/Γ_{52}

This includes $\overline{K}^0 a_1(1260)^+$. The next two entries give the specifically 3-body reaction.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.60±0.10±0.17	90	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+\ \text{3-body})/\Gamma_{\text{total}}$ Γ_{91}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.004	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+\ \text{3-body})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{91}/Γ_{52}

VALUE	DOCUMENT ID	TECN	COMMENT
0.07±0.04±0.06	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^0 f_0(980)\pi^+)/\Gamma_{\text{total}}$ Γ_{92}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.005	90	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\ \text{nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{58}/Γ_{52}

VALUE	DOCUMENT ID	TECN	COMMENT
0.12±0.06 OUR AVERAGE			
0.10±0.04 ±0.06	ANJOS 92C	E691	γBe 90–260 GeV
0.17±0.056±0.100	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{59}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.0037^{+0.0012}_{-0.0010}$	[46] BARLAG 92C	ACCM	π^- Cu 230 GeV

[46] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{59}/Γ_{34}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.080±0.009 OUR FIT				
0.083±0.009 OUR AVERAGE				
0.077±0.008±0.010	239	FRABETTI 97C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
0.09 ±0.01 ±0.01	113	ANJOS 90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)$ Γ_{93}/Γ_{59}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
1.1 ±0.4 OUR FIT Error includes scale factor of 1.8.			
1.25±0.12±0.23	ANJOS 90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\rho^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{94}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
$0.032^{+0.019}_{-0.017}$ OUR FIT Error includes scale factor of 1.8.			
0.023±0.010±0.006	FRABETTI 97C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\pi^+)/\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)$ Γ_{94}/Γ_{93}

VALUE	DOCUMENT ID	TECN	COMMENT
$0.36^{+0.24}_{-0.20}$ OUR FIT Error includes scale factor of 1.8.			
0.75±0.17±0.19	ANJOS 90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-\text{ no-}\rho)/\Gamma(K^-\pi^+\pi^+)$ Γ_{95}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.048\pm0.015\pm0.011$	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma\approx$ 200 GeV

$\Gamma(K^-\rho^0\pi^+\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{63}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
$0.034\pm0.009\pm0.005$	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma\approx$ 200 GeV

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-\text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ Γ_{64}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.026	90	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma\approx$ 200 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{65}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.022^{+0.047}_{-0.008}\pm0.004$	1	[47] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.015		[47] BARLAG	92C	ACCM	π^- Cu 230 GeV

[47] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{66}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.054^{+0.030}_{-0.014}$ OUR AVERAGE					
$0.099^{+0.036}_{-0.070}$		[48] BARLAG	92C	ACCM	π^- Cu 230 GeV
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[48] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[48] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_{67}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0008 ± 0.0007	[49] BARLAG	92C	ACCM	π^- Cu 230 GeV

[49] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{68}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0020 ± 0.0018	[50] BARLAG	92C	ACCM	π^- Cu 230 GeV

[50] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^0\overline{K}^0K^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{69}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.20 ± 0.09 OUR AVERAGE Error includes scale factor of 2.4.					
$0.14\pm0.04\pm0.02$	39	ALBRECHT	94I	ARG	$e^+e^-\approx$ 10 GeV
0.34 ± 0.07	70	AMMAR	91	CLEO	$e^+e^-\approx$ 10.5 GeV

—— Pionic modes ——

$\Gamma(\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{97}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.028\pm0.006\pm0.005$	34	SELEN	93	CLE2	$e^+e^-\approx\Upsilon(4S)$

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{98}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0406 ± 0.0034 OUR FIT					
0.0403 ± 0.0035 OUR AVERAGE					
$0.043\pm0.003\pm0.003$	236	FRABETTI	97D	E687	γ Be $\approx$ 200 GeV
$0.032\pm0.011\pm0.003$	20	ADAMOVICH	93	WA82	π^- 340 GeV
$0.035\pm0.007\pm0.003$		ANJOS	89	E691	Photoproduction
$0.042\pm0.016\pm0.010$	57	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\rho^0\pi^+)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{99}/Γ_{98}

VALUE	DOCUMENT ID		TECN	COMMENT
$0.289\pm0.055\pm0.058$	[51] FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

[51] FRABETTI 97D also includes $f_2(1270)\pi^+$ and $f_0(980)\pi^+$ modes in the fit, but the resulting decay fractions are not statistically significant.

$\Gamma(\rho^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{99}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.015	90	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\text{ nonresonant})/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{100}/Γ_{98}

VALUE	DOCUMENT ID		TECN	COMMENT
0.62 ± 0.11 OUR FIT				
$0.589\pm0.105\pm0.061$	[52] FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

[52] FRABETTI 97D also includes $f_2(1270)\pi^+$ and $f_0(980)\pi^+$ modes in the fit, but the resulting decay fractions are not statistically significant.

$\Gamma(\pi^+\pi^+\pi^-\text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ Γ_{100}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.025 ± 0.005 OUR FIT				
$0.027\pm0.007\pm0.002$	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{101}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.019^{+0.015}_{-0.012}$	[53] BARLAG	92C	ACCM	π^- Cu 230 GeV

[53] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{101}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{106}/Γ_{34}

Unseen decay modes of the η are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.083\pm0.023\pm0.014$		99	DAOUDI	92	CLE2	$e^+e^-\approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.12	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{108}/Γ_{34}

Unseen decay modes of the ω are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_{104}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0010^{+0.0008}_{-0.0007}$	[54] BARLAG	92C	ACCM	π^- Cu 230 GeV

[54] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{104}/Γ_{34}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.023\pm0.004\pm0.002$		58	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma\approx$ 200 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.019	90		ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{109}/Γ_{34}

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	DAOUDI	92	CLE2	$e^+e^-\approx$ 10.5 GeV

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{105}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0029^{+0.0029}_{-0.0020}$	[55] BARLAG	92C	ACCM	π^- Cu 230 GeV

[55] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\eta'(958)\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{110}/Γ_{34}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	DAOUDI	92	CLE2	$e^+e^-\approx$ 10.5 GeV
<0.1	90	ALVAREZ	91	NA14	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.13	90	ANJOS	91B	E691	γBe, $\overline{E}_\gamma\approx$ 145 GeV

$\Gamma(\eta'(958)\rho^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{111}/Γ_{34}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	DAOUDI	92	CLE2	$e^+e^-\approx$ 10.5 GeV

—— Hadronic modes with a $K\overline{K}$ pair ——

$\Gamma(K^+\overline{K}^0)/\Gamma(\overline{K}^0\pi^+)$ Γ_{112}/Γ_{33}

It is generally assumed for modes such as $D^+\to\overline{K}^0\pi^+$ that

$$\Gamma(D^+\to\overline{K}^0\pi^+) = 2\Gamma(D^+\to K^0_S\pi^+);$$

It is the latter Γ that is actually measured. BIGI 95 points out that interference between Cabibbo-allowed and doubly Cabibbo-suppressed amplitudes, where both occur, could invalidate this assumption by a few percent.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.285 ± 0.029 OUR FIT					
0.263 ± 0.035 OUR AVERAGE					
$0.25\pm0.04\pm0.02$	129	FRABETTI	95	E687	γBe $\overline{E}_\gamma\approx$ 200 GeV
$0.271\pm0.065\pm0.039$	69	ANJOS	90C	E691	γBe
$0.317\pm0.086\pm0.048$	31	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV
0.25 ± 0.15	6	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.222\pm0.041\pm0.029$	70	[56] BISHAI	97	CLE2	$e^+e^-\approx\Upsilon(4S)$

[56] This BISHAI 97 result is redundant with results elsewhere in the Listings.

$\Gamma(K^+\overline{K}^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{112}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.082±0.010 OUR FIT					
0.077±0.014±0.007	70	[57] BISHAI	97	CLE2	$e^+e^- \approx \Upsilon(4S)$

[57] See BISHAI 97 for an isospin analysis of $D^+ \rightarrow K\overline{K}$ amplitudes.

$\Gamma(K^+K^-\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{113}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.0976±0.0042±0.0046	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(\phi\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{130}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.068±0.005 OUR AVERAGE					
0.058±0.006±0.006		FRABETTI	95B	E687	Dalitz plot analysis
0.062±0.017±0.006	19	ADAMOVICH	93	WA82	π^- 340 GeV
0.077±0.011±0.005	128	DAOUDI	92	CLE2	$e^+e^- \approx$ 10.5 GeV
0.098±0.032±0.014	12	ALVAREZ	90C	NA14	Photoproduction
0.071±0.008±0.007	84	ANJOS	88	E691	Photoproduction
0.084±0.021±0.011	21	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{134}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.047±0.005 OUR AVERAGE	Error includes scale factor of 1.2.				
0.044±0.003±0.004		[58] FRABETTI	95B	E687	Dalitz plot analysis
0.058±0.009±0.006	73	ANJOS	88	E691	Photoproduction
0.048±0.021±0.011	14	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

[58] See FRABETTI 95B for evidence also of $\overline{K}^*_0(1430)^0K^+$ in the $D^+ \rightarrow K^+K^-\pi^+$ Dalitz plot.

$\Gamma(K^+K^-\pi^+ \text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ Γ_{116}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.050±0.009 OUR AVERAGE					
0.049±0.008±0.006	95	ANJOS	88	E691	Photoproduction
0.059±0.026±0.009	37	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\overline{K}^0\pi^+)$ Γ_{135}/Γ_{33}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.1±0.3±0.4	67	FRABETTI	95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_{131}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.023±0.010	[59] BARLAG	92C	ACCM	π^- Cu 230 GeV

[59] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{131}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.58	90	ALVAREZ	90C	NA14	Photoproduction
<0.28	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{132}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	DAOUDI	92	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0 \text{ non-}\phi)/\Gamma_{\text{total}}$ Γ_{122}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.015^{+0.007}_{-0.006}$	[60] BARLAG	92C	ACCM	π^- Cu 230 GeV

[60] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+\pi^0 \text{ non-}\phi)/\Gamma(K^-\pi^+\pi^+)$ Γ_{122}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	90	ANJOS	89E	E691	Photoproduction

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{123}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_{124}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.01 ±0.005±0.003	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[61] BARLAG	92C	ACCM	π^- Cu 230 GeV

[61] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^*(892)^+\overline{K}^*(892)^0)/\Gamma_{\text{total}}$ Γ_{136}/Γ

Unseen decay modes of the $K^*(892)$'s are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.026±0.008±0.007	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+ \text{ non-}K^{*+}\overline{K}^{*0})/\Gamma_{\text{total}}$ Γ_{126}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0079	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{133}/Γ

Unseen decay modes of the ϕ are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.002	90	0	ANJOS	88	E691	Photoproduction

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{133}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.031	90	ALVAREZ	90C	NA14	Photoproduction

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ $\Gamma_{133}/\Gamma_{130}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	FRABETTI	92	E687	γBe

$\Gamma(K^+K^-\pi^+\pi^+\pi^- \text{ nonresonant})/\Gamma_{\text{total}}$ Γ_{129}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.03	90	12	ANJOS	88	E691	Photoproduction

——— Rare or forbidden modes ———

$\Gamma(K^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{137}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0075±0.0016 OUR AVERAGE					
0.0077±0.0017±0.0008	59	AITALA	97C	E791	π^- nucleus, 500 GeV
0.0072±0.0023±0.0017	21	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+\rho^0)/\Gamma(K^+\pi^+\pi^-)$ $\Gamma_{138}/\Gamma_{137}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.37±0.14±0.07	AITALA	97C	E791	π^- nucleus, 500 GeV

$\Gamma(K^+\rho^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{138}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0067	90	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^*(892)^0\pi^+)/\Gamma(K^+\pi^+\pi^-)$ $\Gamma_{139}/\Gamma_{137}$

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.53±0.21±0.02	AITALA	97C	E791	π^- nucleus, 500 GeV

$\Gamma(K^*(892)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{139}/Γ_{34}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0021	90	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+\pi^+\pi^- \text{ nonresonant})/\Gamma(K^+\pi^+\pi^-)$ $\Gamma_{140}/\Gamma_{137}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.36±0.14±0.07	AITALA	97C	E791	π^- nucleus, 500 GeV

$\Gamma(K^+K^+K^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{141}/Γ_{34}

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0016	90		[62] FRABETTI	95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.057 ±0.020±0.007		13	ADAMOVICH	93	WA82	π^- 340 GeV

[62] Using the $\phi\pi^+$ mode to normalize, FRABETTI 95F gets $\Gamma(K^+K^+K^-)/\Gamma(\phi\pi^+) <$ 0.025.

$\Gamma(\phi K^+)/\Gamma(\phi\pi^+)$ $\Gamma_{142}/\Gamma_{130}$

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.021	90		FRABETTI	95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.058^{+0.032}_{-0.026}\pm0.007$		4	[63] ANJOS	92D	E691	γBe, $\overline{E}_\gamma$ = 145 GeV

[63] The evidence of ANJOS 92D is a small excess of events $(4.5^{+2.4}_{-2.0})$.

$\Gamma(\pi^+ e^+ e^-)/\Gamma_{\text{total}}$ Γ_{143}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<6.6 \times 10^{-5}$	90		AITALA 96	E791	$\pi^- N$ 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1 \times 10^{-4}$	90		FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
$<2.5 \times 10^{-3}$	90		WEIR 90B	MRK2	$e^+ e^-$ 29 GeV
$<2.6 \times 10^{-3}$	90	39	HAAS 88	CLEO	$e^+ e^-$ 10 GeV

$\Gamma(\pi^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{144}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.8 \times 10^{-5}$	90		AITALA 96	E791	$\pi^- N$ 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<8.9 \times 10^{-5}$	90		FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
$<2.2 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV
$<5.9 \times 10^{-3}$	90		WEIR 90B	MRK2	$e^+ e^-$ 29 GeV
$<2.9 \times 10^{-3}$	90	36	HAAS 88	CLEO	$e^+ e^-$ 10 GeV

$\Gamma(\rho^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{145}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<5.6 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^+ e^+ e^-)/\Gamma_{\text{total}}$ Γ_{146}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.0 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.8 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{147}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<9.7 \times 10^{-5}$	90		FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.2 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV
$<9.2 \times 10^{-3}$	90		WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\pi^+ e^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{148}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.3 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\pi^+ e^- \mu^+)/\Gamma_{\text{total}}$ Γ_{149}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.3 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^+ e^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{150}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.4 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^+ e^- \mu^+)/\Gamma_{\text{total}}$ Γ_{151}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.4 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\pi^- e^+ e^+)/\Gamma_{\text{total}}$ Γ_{152}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.8 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{153}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<8.7 \times 10^{-5}$	90		FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.2 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV
$<6.8 \times 10^{-3}$	90		WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\pi^- e^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{154}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.7 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(\rho^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{155}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<5.6 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^- e^+ e^+)/\Gamma_{\text{total}}$ Γ_{156}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9.1 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{157}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90		FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.2 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV
$<4.3 \times 10^{-3}$	90		WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^- e^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{158}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-4}$	90	FRABETTI 97B	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.0 \times 10^{-3}$	90	WEIR 90B	MRK2	$e^+ e^-$ 29 GeV

$\Gamma(K^*(892)^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{159}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<8.5 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$D^\pm$ *CP*-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(K^+ K^- \pi^\pm)$ in $D^\pm \to K^+ K^- \pi^\pm$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID	TECN	COMMENT
−0.017±0.027 OUR AVERAGE			
−0.014±0.029	[64] AITALA 97B	E791	$-0.062 < A_{CP} < +0.034$ (90% CL)
−0.031±0.068	[64] FRABETTI 94I	E687	$-0.14 < A_{CP} < +0.081$ (90% CL)

[64] FRABETTI 94I and AITALA 97B measure $N(D^+ \to K^- K^+ \pi^+)/N(D^+ \to K^- \pi^+ \pi^+)$, the ratio of numbers of events observed, and similarly for the D^-.

$A_{CP}(K^\pm K^{*0})$ in $D^+ \to K^+ \overline{K}^{*0}$ and $D^- \to K^- K^{*0}$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID	TECN	COMMENT
−0.02 ±0.05 OUR AVERAGE			
−0.010±0.050	[65] AITALA 97B	E791	$-0.092 < A_{CP} < +0.072$ (90% CL)
−0.12 ±0.13	[65] FRABETTI 94I	E687	$-0.33 < A_{CP} < +0.094$ (90% CL)

[65] FRABETTI 94I and AITALA 97B measure $N(D^+ \to K^+ \overline{K}^*(892)^0)/N(D^+ \to K^- \pi^+ \pi^+)$, the ratio of numbers of events observed, and similarly for the D^-.

$A_{CP}(\phi \pi^\pm)$ in $D^\pm \to \phi \pi^\pm$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID	TECN	COMMENT
−0.014±0.033 OUR AVERAGE			
−0.028±0.036	[66] AITALA 97B	E791	$-0.087 < A_{CP} < +0.031$ (90% CL)
+0.066±0.086	[66] FRABETTI 94I	E687	$-0.075 < A_{CP} < +0.21$ (90% CL)

[66] FRABETTI 94I and AITALA 97B measure $N(D^+ \to \phi \pi^+)/N(D^+ \to K^- \pi^+ \pi^+)$, the ratio of numbers of events observed, and similarly for the D^-.

$A_{CP}(\pi^+ \pi^- \pi^\pm)$ in $D^\pm \to \pi^+ \pi^- \pi^\pm$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID	TECN	COMMENT
−0.017±0.042	[67] AITALA 97B	E791	$-0.086 < A_{CP} < +0.052$ (90% CL)

[67] AITALA 97B measure $N(D^+ \to \pi^+ \pi^- \pi^+)/N(D^+ \to K^- \pi^+ \pi^+)$, the ratio of numbers of events observed, and similarly for the D^-.

$D^{\pm}$ PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of $D^{\pm}$ mesons at or near the $\psi(3770)$ peak in e^+e^- production.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4.2\ \pm0.6\ \pm0.3$	[68] ADLER	88C	MRK3	e^+e^- 3.768 GeV
$5.5\ \pm1.0$	[69] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
$6.00\pm0.72\pm1.02$	[70] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
$9.1\ \pm2.0$	[71] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[68] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C measure the ratio of cross sections (neutral to charged) to be $1.36 \pm 0.23 \pm 0.14$. This measurement does not include the decays of the $\psi(3770)$ not associated with charmed particle production.

[69] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[70] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[71] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

$D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$ FORM FACTORS

$r_2 \equiv A_2(0)/A_1(0)$ in $D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.72±0.09 OUR AVERAGE					
$0.71\pm0.08\pm0.09$	3000	[72] AITALA	98B	E791	π^- nucleus, 500 GeV
$0.78\pm0.18\pm0.10$	874	[73] FRABETTI	93E	E687	γBe, 220 GeV
$0.82^{+0.22}_{-0.23}\pm0.11$	305	[73] KODAMA	92	E653	$\pi^- N$, 600 GeV
$0.0\ \pm0.5\ \pm0.2$	183	[72] ANJOS	90E	E691	γBe, 90–260 GeV

[72] AITALA 98B and ANJOS 90E use $D^+ \rightarrow \overline{K}^*(892)^0 e^+ \nu_e$ decays.

[73] FRABETTI 93E and KODAMA 92 use $D^+ \rightarrow \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays.

$r_V \equiv V(0)/A_1(0)$ in $D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.85±0.12 OUR AVERAGE					
$1.84\pm0.11\pm0.08$	3000	[74] AITALA	98B	E791	π^- nucleus, 500 GeV
$1.74\pm0.27\pm0.28$	874	[75] FRABETTI	93E	E687	γBe, 220 GeV
$2.00^{+0.34}_{-0.32}\pm0.16$	305	[75] KODAMA	92	E653	$\pi^- N$, 600 GeV
$2.0\ \pm0.6\ \pm0.3$	183	[74] ANJOS	90E	E691	γBe, 90–260 GeV

[74] AITALA 98B and ANJOS 90E use $D^+ \rightarrow \overline{K}^*(892)^0 e^+ \nu_e$ decays.

[75] FRABETTI 93E and KODAMA 92 use $D^+ \rightarrow \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays.

Γ_L/Γ_T in $D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.23±0.13 OUR AVERAGE					
$1.20\pm0.13\pm0.13$	874	[76] FRABETTI	93E	E687	γBe, 220 GeV
$1.18\pm0.18\pm0.08$	305	[76] KODAMA	92	E653	$\pi^- N$, 600 GeV
$1.8\ {}^{+0.6}_{-0.4}\ \pm0.3$	183	[77] ANJOS	90E	E691	γBe, 90–260 GeV

[76] FRABETTI 93E and KODAMA 92 use $D^+ \rightarrow \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays. Γ_L/Γ_T is evaluated for a lepton mass of zero.

[77] ANJOS 90E uses $D^+ \rightarrow \overline{K}^*(892)^0 e^+ \nu_e$ decays.

Γ_+/Γ_- in $D^+ \rightarrow \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.16±0.04 OUR AVERAGE					
$0.16\pm0.05\pm0.02$	305	[78] KODAMA	92	E653	$\pi^- N$, 600 GeV
$0.15^{+0.07}_{-0.05}\pm0.03$	183	[79] ANJOS	90E	E691	γBe, 90–260 GeV

[78] KODAMA 92 uses $D^+ \rightarrow \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays. Γ_+/Γ_- is evaluated for a lepton mass of zero.

[79] ANJOS 90E uses $D^+ \rightarrow \overline{K}^*(892)^0 e^+ \nu_e$ decays.

$D^{\pm}$ REFERENCES

AITALA	98B	PRL 80 1393	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
PDG	98	EPJ C3 1	C. Caso+	
AITALA	97	PL B397 325	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
AITALA	97B	PL B403 377	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
AITALA	97C	PL B404 187	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
BARTELT	97	PL B405 373	+Csorna, Jain, Marka+	(CLEO Collab.)
BISHAI	97	PRL 78 3261	+Fast, Gerndt, Hinson+	(CLEO Collab.)
FRABETTI	97	PL B391 235	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	97B	PL B398 239	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	97C	PL B401 131	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	97D	PL B407 79	+Cheung, Cumalat+	(FNAL E687 Collab.)
AITALA	96	PRL 76 364	+Amato, Anjos+	(FNAL E791 Collab.)
ALBRECHT	96C	PL B374 249	+Hamacher, Hofmann+	(ARGUS Collab.)
BIGI	95	PL B349 363	+Yamamoto	(NDAM, HARV)
FRABETTI	95	PL B346 199	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95B	PL B351 591	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95E	PL B359 403	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95F	PL B363 259	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	94I	ZPHY C64 375	+Hamacher, Hofmann+	(ARGUS Collab.)
ALEEV	94	PAN 57 1370 Translated from YF 57 1443.	+Balandin+	(Serpukhov BIS-2 Collab.)
BALEST	94	PRL 72 2328	+Cho, Daoudi, Ford+	(CLEO Collab.)
FRABETTI	94D	PL B323 459	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94G	PL B331 217	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94I	PR D50 R2953	+Cheung, Cumalat+	(FNAL E687 Collab.)
ABE	93E	PL B313 288	+Amako, Arai, Arima, Asano+	(VENUS Collab.)
ADAMOVICH	93	PL B305 177	+Alexandrov, Antinori+	(CERN WA82 Collab.)
AKERIB	93	PRL 71 3070	+Barish, Chadha, Chan+	(CLEO Collab.)
ALAM	93	PRL 71 1311	+Kim, Nemati, O'Neill+	(CLEO Collab.)
ANJOS	93	PR D48 56	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
BEAN	93C	PL B317 647	+Gronberg, Kutschke, Menary+	(CLEO Collab.)
FRABETTI	93E	PL B307 262	+Grim, Paolone, Yager+	(FNAL E687 Collab.)
KODAMA	93B	PL B313 260	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
KODAMA	93C	PL B316 455	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
SELEN	93	PRL 71 1973	+Sadoff, Ammar, Ball+	(CLEO Collab.)
ALBRECHT	92B	ZPHY C53 361	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALBRECHT	92F	PL B278 202	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ANJOS	92	PR D45 R2177	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	92C	PR D46 1941	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	92D	PRL 69 2892	+Appel, Bean, Bediaga+	(FNAL E691 Collab.)
BARLAG	92C	ZPHY C55 383	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
Also	90D	ZPHY C48 29	Barlag, Becker, Boehringer, Bosman+	(ACCMOR Collab.)
COFFMAN	92B	PR D45 2196	+DeJongh, Dubois, Eigen+	(Mark III Collab.)
DAOUDI	92	PR D45 3965	+Ford, Johnson, Lingel+	(CLEO Collab.)
FRABETTI	92	PL B281 167	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
KODAMA	92	PL B274 246	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
KODAMA	92C	PL B286 187	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ADAMOVICH	91	PL B268 142	+Alexandrov, Antinori, Barberis+	(WA82 Collab.)
ALBRECHT	91	PL B255 634	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALVAREZ	91	PL B255 639	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	91B	ZPHY C50 11	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
AMMAR	91	PR D44 3383	+Baringer, Coppage, Davis+	(CLEO Collab.)
ANJOS	91B	PR D43 R2063	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	91C	PRL 67 1507	+Appel, Bean, Bracker+	(FNAL-TPS Collab.)
BAI	91	PRL 66 1011	+Bolton, Brown, Bunnell+	(Mark III Collab.)
COFFMAN	91	PL B263 135	+DeJongh, Dubois, Eigen, Hitlin+	(Mark III Collab.)
FRABETTI	91	PL B263 584	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	90C	PL B246 261	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90C	PR D41 2705	+Appel, Bean+	(FNAL E691 Collab.)
ANJOS	90D	PR D42 2414	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	90E	PRL 65 2630	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
BARLAG	90C	ZPHY C46 563	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
WEIR	90B	PR D41 1384	+Klein, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
ANJOS	89	PRL 62 125	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	89B	PRL 62 722	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	89E	PL B223 267	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ADLER	88B	PRL 60 1375	+Becker, Blaylock+	(Mark III Collab.)
ADLER	88C	PRL 60 89	+Becker, Blaylock+	(Mark III Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88	PRL 60 897	+Appel+	(FNAL E691 Collab.)
AOKI	88	PL B209 113	+Arnold, Baroni+	(WA75 Collab.)
HAAS	88	PRL 60 1614	+Hempstead, Jensen+	(CLEO Collab.)
ONG	88	PRL 60 2587	+Weir, Abrams, Amidei+	(Mark II Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL E691 Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
ADLER	87	PL B196 107	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AGUILAR-...	87D	PL B193 140	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
AGUILAR-...	87E	ZPHY C36 551	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
AGUILAR-...	87F	ZPHY C36 559	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88	ZPHY C38 520 erratum		
BARLAG	87B	ZPHY C37 17	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
BARTEL	87	ZPHY C33 339	+Becker, Felst, Haidt+	(JADE Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
PALKA	87B	ZPHY C35 151	+Bailey, Becker+	(ACCMOR Collab.)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
AGUILAR-...	86B	ZPHY C31 491	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
BALTRUSAIT...	86E	PRL 56 2140	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
PAL	86	PR D33 2708	+Atwood, Barish, Bonneaud+	(DELCO Collab.)
AIHARA	85	ZPHY C27 39	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
BALTRUSAIT...	85B	PRL 54 1976	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BALTRUSAIT...	85E	PRL 55 150	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BARTEL	85J	PL 163B 277	+Becker, Cords, Felst+	(JADE Collab.)
ADAMOVICH	84	PL 140B 119	+Alexandrov, Bolta, Bravo+	(CERN WA58 Collab.)
ALTHOFF	84G	ZPHY C22 219	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84J	PL 146B 443	+Branschweig, Kirschfink+	(TASSO Collab.)
DERRICK	84	PRL 53 1971	+Fernandez, Fries, Hyman+	(HRS Collab.)
KOOP	84	PRL 52 970	+Sakuda, Atwood, Baillon+	(DELCO Collab.)
PARTRIDGE	84	Thesis CALT-68-1150		(Crystal Ball Collab.)
AGUILAR-...	83B	PL 123B 98	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AUBERT	83	NP B213 31	+Bassompierre, Becks, Best+	(EMC Collab.)
PARTRIDGE	81	PRL 47 760	+Peck, Porter, Gu+	(Crystal Ball Collab.)
SCHINDLER	81	PR D24 78	+Alam, Boyarski, Breidenbach+	(Mark II Collab.)
TRILLING	81	PRPL 75 57		(LBL, UCB) J
BACINO	80	PRL 45 329	+Ferguson+	(DELCO Collab.)
SCHINDLER	80	PR D21 2716	+Siegrist, Alam, Boyarski+	(Mark II Collab.)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)

BACINO	79	PRL 43 1073	+Ferguson, Nodulman+	(DELCO Collab.)
BRANDELIK	79	PL 80B 412	+Braunschweig, Martyn, Sander+	(DASP Collab.)
FELLER	78	PRL 40 274	+Litke, Madaras, Ronan+	(Mark I Collab.)
VUILLEMIN	78	PRL 41 1149	+Feldman, Feller+	(Mark I Collab.)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(Mark I Collab.)
PICCOLO	77	PL 70B 260	+Peruzzi, Luth, Nguyen, Wiss, Abrams+	(Mark I Collab.)
RAPIDIS	77	PRL 39 526	+Gobbi, Luke, Barbaro-Galtieri+	(Mark I Collab.)
PERUZZI	76	PRL 37 569	+Piccolo, Feldman, Nguyen, Wiss+	(Mark I Collab.)

OTHER RELATED PAPERS

RICHMAN	95	RMP 67 893	+Burchat	(UCSB, STAN)
ROSNER	95	CNPP 21 369		(CHIC)

D^0

$I(J^P) = \frac{1}{2}(0^-)$

D^0 MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1864.6± 0.5 OUR FIT	Error includes scale factor of 1.1.			
1864.1± 1.0 OUR AVERAGE				
1864.6± 0.3±1.0	641	BARLAG 90C	ACCM	π^- Cu 230 GeV
1852 ± 7	16	ADAMOVICH 87	EMUL	Photoproduction
1861 ± 4		DERRICK 84	HRS	e^+e^- 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1856 ±36	22	ADAMOVICH 84B	EMUL	Photoproduction
1847 ± 7	1	FIORINO 81	EMUL	$\gamma N \to \overline{D}^0 +$
1863.8± 0.5		[1] SCHINDLER 81	MRK2	e^+e^- 3.77 GeV
1864.7± 0.6		[1] TRILLING 81	RVUE	e^+e^- 3.77 GeV
1863.0± 2.5	238	ASTON 80E	OMEG	$\gamma p \to \overline{D}^0$
1860 ± 2	143	[2] AVERY 80	SPEC	$\gamma N \to D^{*+}$
1869 ± 4	35	[2] AVERY 80	SPEC	$\gamma N \to D^{*+}$
1854 ± 6	94	[2] ATIYA 79	SPEC	$\gamma N \to D^0 \overline{D}^0$
1850 ±15	64	BALTAY 78C	HBC	$\nu N \to K^0 \pi\pi$
1863 ± 3		GOLDHABER 77	MRK1	D^0, D^+ recoil spectra
1863.3± 0.9		[1] PERUZZI 77	MRK1	e^+e^- 3.77 GeV
1868 ±11		PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV
1865 ±15	234	GOLDHABER 76	MRK1	$K\pi$ and $K3\pi$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted. TRILLING 81 enters the fit in the $D^{\pm}$ mass, and PERUZZI 77 and SCHINDLER 81 enter in the $m_{D^{\pm}} - m_{D^0}$, below.

[2] Error does not include possible systematic mass scale shift, estimated to be less than 5 MeV.

$m_{D^{\pm}} - m_{D^0}$

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4.76±0.10 OUR FIT	Error includes scale factor of 1.1.		
4.74±0.28 OUR AVERAGE			
4.7 ±0.3	[3] SCHINDLER 81	MRK2	e^+e^- 3.77 GeV
5.0 ±0.8	[3] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[3] See the footnote on TRILLING 81 in the D^0 and $D^{\pm}$ sections on the mass.

D^0 MEAN LIFE

Measurements with an error $> 0.05 \times 10^{-12}$ s are omitted from the average, and those with an error $> 0.1 \times 10^{-12}$ s or that have been superseded by later results have been removed from the Listings.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
0.415±0.004 OUR AVERAGE				
0.413±0.004±0.003	16k	FRABETTI 94D	E687	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
0.424±0.011±0.007	5118	FRABETTI 91	E687	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
0.417±0.018±0.015	890	ALVAREZ 90	NA14	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
$0.388^{+0.023}_{-0.021}$	641	[4] BARLAG 90C	ACCM	π^- Cu 230 GeV
0.48 ±0.04 ±0.03	776	ALBRECHT 88I	ARG	e^+e^- 10 GeV
0.422±0.008±0.010	4212	RAAB 88	E691	Photoproduction
0.42 ±0.05	90	BARLAG 87B	ACCM	K^- and π^- 200 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.34\,^{+0.06}_{-0.05}\pm 0.03$	58	AMENDOLIA 88	SPEC	Photoproduction
$0.46\,^{+0.06}_{-0.05}$	145	AGUILAR-... 87D	HYBR	$\pi^- p$ and pp
0.50 ±0.07 ±0.04	317	CSORNA 87	CLEO	e^+e^- 10 GeV
0.61 ±0.09 ±0.03	50	ABE 86	HYBR	γp 20 GeV
$0.47\,^{+0.09}_{-0.08}\pm 0.05$	74	GLADNEY 86	MRK2	e^+e^- 29 GeV
$0.43\,^{+0.07}_{-0.05}\,^{+0.01}_{-0.02}$	58	USHIDA 86B	EMUL	ν wideband
$0.37\,^{+0.10}_{-0.07}$	26	BAILEY 85	SILI	π^- Be 200 GeV

[4] BARLAG 90C estimate systematic error to be negligible.

$\left|m_{D_1^0} - m_{D_2^0}\right|$

The D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson. To calculate the following limits, we use $\Delta m = [2r/(1-r)]^{1/2}\hbar/4.15 \times 10^{-13}$ s, where r is the experimental D^0-$\overline{D}^0$ mixing ratio.

VALUE ($10^{10}\ \hbar\ \text{s}^{-1}$)	CL%	DOCUMENT ID	TECN	COMMENT
<24	90	[5] AITALA 96C	E791	π^- nucleus, 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<32	90	[6,7] AITALA 98	E791	π^- nucleus, 500 GeV
<21	90	[7,8] ANJOS 88C	E691	Photoproduction

[5] This limit is inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via }\overline{D}^0))/\Gamma(K^-\ell^+\nu_\ell)$ given near the end of the D^0 Listings.

[6] AITALA 98 allows interference between the doubly Cabibbo-suppressed and mixing amplitudes, and also allows CP violation in this term.

[7] This limit is inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-\text{or } K^+\pi^-\pi^+\pi^-(\text{via } \overline{D}^0))/\Gamma(K^-\pi^+\text{or } K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings. Decay-time information is used to distinguish doubly Cabibbo-suppressed decays from D^0-$\overline{D}^0$ mixing.

[8] ANJOS 88C assumes no interference between doubly Cabibbo-suppressed and mixing amplitudes. When interference is allowed, the limit degrades by about a factor of two.

$\left|\Gamma_{D_1^0} - \Gamma_{D_2^0}\right|/\Gamma_{D^0}$ MEAN LIFE DIFFERENCE/AVERAGE

The D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson. To calculate the following limits, we use $\Delta\Gamma/\Gamma = [8r/(1+r)]^{1/2}$, where r is the experimental D^0-$\overline{D}^0$ mixing ratio.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.20	90	[9] AITALA 96C	E791	π^- nucleus, 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.26	90	[10,11] AITALA 98	E791	π^- nucleus, 500 GeV
<0.17	90	[11,12] ANJOS 88C	E691	Photoproduction

[9] This limit is inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via }\overline{D}^0))/\Gamma(K^-\ell^+\nu_\ell)$ given near the end of the D^0 Listings.

[10] AITALA 98 allows interference between the doubly Cabibbo-suppressed and mixing amplitudes, and also allows CP violation in this term.

[11] This limit is inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-\text{or } K^+\pi^-\pi^+\pi^-(\text{via } \overline{D}^0))/\Gamma(K^-\pi^+\text{or } K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings. Decay-time information is used to distinguish doubly Cabibbo-suppressed decays from D^0-$\overline{D}^0$ mixing.

[12] ANJOS 88C assumes no interference between doubly Cabibbo-suppressed and mixing amplitudes. When interference is allowed, the limit degrades by about a factor of two.

D^0 DECAY MODES

$\overline{D}^0$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+anything	(6.75±0.29) %	
Γ_2	μ^+anything	(6.6 ±0.8) %	
Γ_3	K^-anything	(53 ±4) %	S=1.3
Γ_4	$\overline{K}^0$anything + K^0anything	(42 ±5) %	
Γ_5	K^+anything	($3.4\,^{+0.6}_{-0.4}$) %	
Γ_6	η anything	[a] < 13 %	CL=90%

Semileptonic modes

Γ_{7}	$K^- \ell^+ \nu_\ell$	[b]	(3.50 ± 0.17) %	S=1.3
Γ_{8}	$K^- e^+ \nu_e$		(3.66 ± 0.18) %	
Γ_{9}	$K^- \mu^+ \nu_\mu$		(3.23 ± 0.17) %	
Γ_{10}	$K^- \pi^0 e^+ \nu_e$		$(1.6 {}^{+1.3}_{-0.5})$ %	
Γ_{11}	$\overline{K}^0 \pi^- e^+ \nu_e$		$(2.8 {}^{+1.7}_{-0.9})$ %	
Γ_{12}	$\overline{K}^*(892)^- e^+ \nu_e$ $\times$ B$(K^{*-} \to \overline{K}^0 \pi^-)$		(1.35 ± 0.22) %	
Γ_{13}	$K^*(892)^- \ell^+ \nu_\ell$		—	
Γ_{14}	$\overline{K}^*(892)^0 \pi^- e^+ \nu_e$		—	
Γ_{15}	$K^- \pi^+ \pi^- \mu^+ \nu_\mu$		$< 1.2 \times 10^{-3}$	CL=90%
Γ_{16}	$(\overline{K}^*(892)\pi)^- \mu^+ \nu_\mu$		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{17}	$\pi^- e^+ \nu_e$		$(3.7 \pm 0.6) \times 10^{-3}$	

A fraction of the following resonance mode has already appeared above as a submode of a charged-particle mode.

Γ_{18}	$K^*(892)^- e^+ \nu_e$		(2.02 ± 0.33) %	

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

Γ_{19}	$K^- \pi^+$		(3.85 ± 0.09) %	
Γ_{20}	$\overline{K}^0 \pi^0$		(2.12 ± 0.21) %	S=1.1
Γ_{21}	$\overline{K}^0 \pi^+ \pi^-$	[c]	(5.4 ± 0.4) %	S=1.2
Γ_{22}	$\overline{K}^0 \rho^0$		(1.21 ± 0.17) %	
Γ_{23}	$\overline{K}^0 f_0(980)$ $\times$ B$(f_0 \to \pi^+ \pi^-)$		$(3.0 \pm 0.8) \times 10^{-3}$	
Γ_{24}	$\overline{K}^0 f_2(1270)$ $\times$ B$(f_2 \to \pi^+ \pi^-)$		$(2.4 \pm 0.9) \times 10^{-3}$	
Γ_{25}	$\overline{K}^0 f_0(1370)$ $\times$ B$(f_0 \to \pi^+ \pi^-)$		$(4.3 \pm 1.3) \times 10^{-3}$	
Γ_{26}	$K^*(892)^- \pi^+$ $\times$ B$(K^{*-} \to \overline{K}^0 \pi^-)$		(3.4 ± 0.3) %	
Γ_{27}	$K_0^*(1430)^- \pi^+$ $\times$ B$(K_0^*(1430)^- \to \overline{K}^0 \pi^-)$		$(6.4 \pm 1.6) \times 10^{-3}$	
Γ_{28}	$\overline{K}^0 \pi^+ \pi^-$ nonresonant		(1.47 ± 0.24) %	
Γ_{29}	$K^- \pi^+ \pi^0$	[c]	(13.9 ± 0.9) %	S=1.3
Γ_{30}	$K^- \rho^+$		(10.8 ± 1.0) %	
Γ_{31}	$K^*(892)^- \pi^+$ $\times$ B$(K^{*-} \to K^- \pi^0)$		(1.7 ± 0.2) %	
Γ_{32}	$\overline{K}^*(892)^0 \pi^0$ $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$		(2.1 ± 0.3) %	
Γ_{33}	$K^- \pi^+ \pi^0$ nonresonant		$(6.9 \pm 2.5) \times 10^{-3}$	
Γ_{34}	$\overline{K}^0 \pi^0 \pi^0$		—	
Γ_{35}	$\overline{K}^*(892)^0 \pi^0$ $\times$ B$(\overline{K}^{*0} \to \overline{K}^0 \pi^0)$		(1.1 ± 0.2) %	
Γ_{36}	$\overline{K}^0 \pi^0 \pi^0$ nonresonant		$(7.9 \pm 2.1) \times 10^{-3}$	
Γ_{37}	$K^- \pi^+ \pi^+ \pi^-$	[c]	(7.6 ± 0.4) %	S=1.1
Γ_{38}	$K^- \pi^+ \rho^0$ total		(6.3 ± 0.4) %	
Γ_{39}	$K^- \pi^+ \rho^0$ 3-body		$(4.8 \pm 2.1) \times 10^{-3}$	
Γ_{40}	$\overline{K}^*(892)^0 \rho^0$ $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$		$(9.8 \pm 2.2) \times 10^{-3}$	
Γ_{41}	$K^- a_1(1260)^+$ $\times$ B$(a_1(1260)^+ \to \pi^+ \pi^+ \pi^-)$		(3.6 ± 0.6) %	
Γ_{42}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ total $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$		(1.5 ± 0.4) %	
Γ_{43}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$		$(9.5 \pm 2.1) \times 10^{-3}$	
Γ_{44}	$K_1(1270)^- \pi^+$ $\times$ B$(K_1(1270)^- \to K^- \pi^+ \pi^-)$	[d]	$(3.6 \pm 1.0) \times 10^{-3}$	
Γ_{45}	$K^- \pi^+ \pi^+ \pi^-$ nonresonant		(1.76 ± 0.25) %	
Γ_{46}	$\overline{K}^0 \pi^+ \pi^- \pi^0$	[c]	(10.0 ± 1.2) %	
Γ_{47}	$\overline{K}^0 \eta \times$ B$(\eta \to \pi^+ \pi^- \pi^0)$		$(1.6 \pm 0.3) \times 10^{-3}$	
Γ_{48}	$\overline{K}^0 \omega \times$ B$(\omega \to \pi^+ \pi^- \pi^0)$		(1.9 ± 0.4) %	
Γ_{49}	$K^*(892)^- \rho^+$ $\times$ B$(K^{*-} \to \overline{K}^0 \pi^-)$		(4.1 ± 1.6) %	
Γ_{50}	$\overline{K}^*(892)^0 \rho^0$ $\times$ B$(\overline{K}^{*0} \to \overline{K}^0 \pi^0)$		$(4.9 \pm 1.1) \times 10^{-3}$	
Γ_{51}	$K_1(1270)^- \pi^+$ $\times$ B$(K_1(1270)^- \to \overline{K}^0 \pi^- \pi^0)$	[d]	$(5.1 \pm 1.4) \times 10^{-3}$	
Γ_{52}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body $\times$ B$(\overline{K}^{*0} \to \overline{K}^0 \pi^0)$		$(4.8 \pm 1.1) \times 10^{-3}$	
Γ_{53}	$\overline{K}^0 \pi^+ \pi^- \pi^0$ nonresonant		(2.1 ± 2.1) %	
Γ_{54}	$K^- \pi^+ \pi^0 \pi^0$		(15 ± 5) %	
Γ_{55}	$K^- \pi^+ \pi^+ \pi^- \pi^0$		(4.1 ± 0.4) %	
Γ_{56}	$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$ $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$		(1.2 ± 0.6) %	
Γ_{57}	$\overline{K}^*(892)^0 \eta$ $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$ $\times$ B$(\eta \to \pi^+ \pi^- \pi^0)$		$(2.9 \pm 0.8) \times 10^{-3}$	
Γ_{58}	$K^- \pi^+ \omega \times$ B$(\omega \to \pi^+ \pi^- \pi^0)$		(2.7 ± 0.5) %	
Γ_{59}	$\overline{K}^*(892)^0 \omega$ $\times$ B$(\overline{K}^{*0} \to K^- \pi^+)$ $\times$ B$(\omega \to \pi^+ \pi^- \pi^0)$		$(7 \pm 3) \times 10^{-3}$	
Γ_{60}	$\overline{K}^0 \pi^+ \pi^+ \pi^- \pi^-$		$(5.8 \pm 1.6) \times 10^{-3}$	
Γ_{61}	$\overline{K}^0 \pi^+ \pi^- \pi^0 \pi^0 (\pi^0)$		$(10.6 {}^{+7.3}_{-3.0})$ %	
Γ_{62}	$\overline{K}^0 K^+ K^-$		$(9.4 \pm 1.0) \times 10^{-3}$	

In the fit as $\frac{1}{2}\Gamma_{74} + \Gamma_{64}$, where $\frac{1}{2}\Gamma_{74} = \Gamma_{63}$.

Γ_{63}	$\overline{K}^0 \phi \times$ B$(\phi \to K^+ K^-)$		$(4.3 \pm 0.5) \times 10^{-3}$	
Γ_{64}	$\overline{K}^0 K^+ K^-$ non-ϕ		$(5.1 \pm 0.8) \times 10^{-3}$	
Γ_{65}	$K_S^0 K_S^0 K_S^0$		$(8.4 \pm 1.5) \times 10^{-4}$	
Γ_{66}	$K^+ K^- K^- \pi^+$		$(2.1 \pm 0.5) \times 10^{-4}$	
Γ_{67}	$K^+ K^- \overline{K}^0 \pi^0$		$(7.2 {}^{+4.8}_{-3.5}) \times 10^{-3}$	

Fractions of many of the following modes with resonances have already appeared above as submodes of particular charged-particle modes. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)

Γ_{68}	$\overline{K}^0 \eta$		$(7.1 \pm 1.0) \times 10^{-3}$	
Γ_{69}	$\overline{K}^0 \rho^0$		(1.21 ± 0.17) %	
Γ_{70}	$K^- \rho^+$		(10.8 ± 1.0) %	S=1.2
Γ_{71}	$\overline{K}^0 \omega$		(2.1 ± 0.4) %	
Γ_{72}	$\overline{K}^0 \eta'(958)$		(1.72 ± 0.26) %	
Γ_{73}	$\overline{K}^0 f_0(980)$		$(5.7 \pm 1.6) \times 10^{-3}$	
Γ_{74}	$\overline{K}^0 \phi$		$(8.6 \pm 1.0) \times 10^{-3}$	
Γ_{75}	$K^- a_1(1260)^+$		(7.3 ± 1.1) %	
Γ_{76}	$\overline{K}^0 a_1(1260)^0$		< 1.9 %	CL=90%
Γ_{77}	$\overline{K}^0 f_2(1270)$		$(4.2 \pm 1.5) \times 10^{-3}$	
Γ_{78}	$K^- a_2(1320)^+$		$< 2 \times 10^{-3}$	CL=90%
Γ_{79}	$\overline{K}^0 f_0(1370)$		$(7.0 \pm 2.1) \times 10^{-3}$	
Γ_{80}	$K^*(892)^- \pi^+$		(5.1 ± 0.4) %	S=1.2
Γ_{81}	$\overline{K}^*(892)^0 \pi^0$		(3.2 ± 0.4) %	
Γ_{82}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ total		(2.3 ± 0.5) %	
Γ_{83}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body		(1.43 ± 0.32) %	
Γ_{84}	$K^- \pi^+ \rho^0$ total		(6.3 ± 0.4) %	
Γ_{85}	$K^- \pi^+ \rho^0$ 3-body		$(4.8 \pm 2.1) \times 10^{-3}$	
Γ_{86}	$\overline{K}^*(892)^0 \rho^0$		(1.47 ± 0.33) %	
Γ_{87}	$\overline{K}^*(892)^0 \rho^0$ transverse		(1.5 ± 0.5) %	
Γ_{88}	$\overline{K}^*(892)^0 \rho^0$ *S*-wave		(2.8 ± 0.6) %	
Γ_{89}	$\overline{K}^*(892)^0 \rho^0$ *S*-wave long.		$< 3 \times 10^{-3}$	CL=90%
Γ_{90}	$\overline{K}^*(892)^0 \rho^0$ *P*-wave		$< 3 \times 10^{-3}$	CL=90%
Γ_{91}	$\overline{K}^*(892)^0 \rho^0$ *D*-wave		(1.9 ± 0.6) %	
Γ_{92}	$K^*(892)^- \rho^+$		(6.1 ± 2.4) %	
Γ_{93}	$K^*(892)^- \rho^+$ longitudinal		(2.9 ± 1.2) %	
Γ_{94}	$K^*(892)^- \rho^+$ transverse		(3.2 ± 1.8) %	
Γ_{95}	$K^*(892)^- \rho^+$ *P*-wave		< 1.5 %	CL=90%
Γ_{96}	$K^- \pi^+ f_0(980)$		< 1.1 %	CL=90%
Γ_{97}	$\overline{K}^*(892)^0 f_0(980)$		$< 7 \times 10^{-3}$	CL=90%
Γ_{98}	$K_1(1270)^- \pi^+$	[d]	(1.06 ± 0.29) %	
Γ_{99}	$K_1(1400)^- \pi^+$		< 1.2 %	CL=90%
Γ_{100}	$\overline{K}_1(1400)^0 \pi^0$		< 3.7 %	CL=90%
Γ_{101}	$K^*(1410)^- \pi^+$		< 1.2 %	CL=90%
Γ_{102}	$K_0^*(1430)^- \pi^+$		(1.04 ± 0.26) %	
Γ_{103}	$K_2^*(1430)^- \pi^+$		$< 8 \times 10^{-3}$	CL=90%
Γ_{104}	$\overline{K}_2^*(1430)^0 \pi^0$		$< 4 \times 10^{-3}$	CL=90%
Γ_{105}	$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$		(1.8 ± 0.9) %	
Γ_{106}	$\overline{K}^*(892)^0 \eta$		(1.9 ± 0.5) %	
Γ_{107}	$K^- \pi^+ \omega$		(3.0 ± 0.6) %	
Γ_{108}	$\overline{K}^*(892)^0 \omega$		(1.1 ± 0.5) %	
Γ_{109}	$K^- \pi^+ \eta'(958)$		$(7.0 \pm 1.8) \times 10^{-3}$	
Γ_{110}	$\overline{K}^*(892)^0 \eta'(958)$		$< 1.1 \times 10^{-3}$	CL=90%

Pionic modes

Γ_{111}	$\pi^+\pi^-$		$(1.53\pm0.09)\times10^{-3}$	
Γ_{112}	$\pi^0\pi^0$		$(8.5\ \pm2.2\ )\times10^{-4}$	
Γ_{113}	$\pi^+\pi^-\pi^0$		$(1.6\ \pm1.1\ )$ %	S=2.7
Γ_{114}	$\pi^+\pi^+\pi^-\pi^-$		$(7.4\ \pm0.6\ )\times10^{-3}$	
Γ_{115}	$\pi^+\pi^+\pi^-\pi^-\pi^0$		$(1.9\ \pm0.4\ )$ %	
Γ_{116}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$		$(4.0\ \pm3.0\ )\times10^{-4}$	

Hadronic modes with a $K\overline{K}$ pair

Γ_{117}	K^+K^-		$(4.27\pm0.16)\times10^{-3}$	
Γ_{118}	$K^0\overline{K}^0$		$(6.5\ \pm1.8\ )\times10^{-4}$	S=1.2
Γ_{119}	$K^0K^-\pi^+$		$(6.4\ \pm1.0\ )\times10^{-3}$	S=1.1
Γ_{120}	$\overline{K}^*(892)^0K^0 \times B(\overline{K}^{*0}\rightarrow K^-\pi^+)$		$< 1.1 \times10^{-3}$	CL=90%
Γ_{121}	$K^*(892)^+K^- \times B(K^{*+}\rightarrow K^0\pi^+)$		$(2.3\ \pm0.5\ )\times10^{-3}$	
Γ_{122}	$K^0K^-\pi^+$ nonresonant		$(2.3\ \pm2.3\ )\times10^{-3}$	
Γ_{123}	$\overline{K}^0K^+\pi^-$		$(5.0\ \pm1.0\ )\times10^{-3}$	
Γ_{124}	$K^*(892)^0\overline{K}^0 \times B(K^{*0}\rightarrow K^+\pi^-)$		$< 5 \times10^{-4}$	CL=90%
Γ_{125}	$K^*(892)^-K^+ \times B(K^{*-}\rightarrow \overline{K}^0\pi^-)$		$(1.2\ \pm0.7\ )\times10^{-3}$	
Γ_{126}	$\overline{K}^0K^+\pi^-$ nonresonant		$(3.9\ {}^{+2.3}_{-1.9})\times10^{-3}$	
Γ_{127}	$K^+K^-\pi^0$		$(1.3\ \pm0.4\ )\times10^{-3}$	
Γ_{128}	$K^0_SK^0_S\pi^0$		$< 5.9 \times10^{-4}$	
Γ_{129}	$K^+K^-\pi^+\pi^-$	[e]	$(2.52\pm0.24)\times10^{-3}$	
Γ_{130}	$\phi\pi^+\pi^- \times B(\phi\rightarrow K^+K^-)$		$(5.3\ \pm1.4\ )\times10^{-4}$	
Γ_{131}	$\phi\rho^0 \times B(\phi\rightarrow K^+K^-)$		$(3.0\ \pm1.6\ )\times10^{-4}$	
Γ_{132}	$K^+K^-\rho^0$ 3-body		$(9.1\ \pm2.3\ )\times10^{-4}$	
Γ_{133}	$K^*(892)^0K^-\pi^+$+c.c. $\times B(K^{*0}\rightarrow K^+\pi^-)$	[f]	$< 5 \times10^{-4}$	
Γ_{134}	$K^*(892)^0\overline{K}^*(892)^0 \times B^2(K^{*0}\rightarrow K^+\pi^-)$		$(6\ \pm2\ )\times10^{-4}$	
Γ_{135}	$K^+K^-\pi^+\pi^-$ non-ϕ		—	
Γ_{136}	$K^+K^-\pi^+\pi^-$ nonresonant		$< 8 \times10^{-4}$	CL=90%
Γ_{137}	$K^0\overline{K}^0\pi^+\pi^-$		$(6.9\ \pm2.7\ )\times10^{-3}$	
Γ_{138}	$K^+K^-\pi^+\pi^-\pi^0$		$(3.1\ \pm2.0\ )\times10^{-3}$	

Fractions of most of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{139}	$\overline{K}^*(892)^0K^0$		$< 1.6 \times10^{-3}$	CL=90%
Γ_{140}	$K^*(892)^+K^-$		$(3.5\ \pm0.8\ )\times10^{-3}$	
Γ_{141}	$K^*(892)^0\overline{K}^0$		$< 8 \times10^{-4}$	CL=90%
Γ_{142}	$K^*(892)^-K^+$		$(1.8\ \pm1.0\ )\times10^{-3}$	
Γ_{143}	$\phi\pi^0$		$< 1.4 \times10^{-3}$	CL=90%
Γ_{144}	$\phi\eta$		$< 2.8 \times10^{-3}$	CL=90%
Γ_{145}	$\phi\omega$		$< 2.1 \times10^{-3}$	CL=90%
Γ_{146}	$\phi\pi^+\pi^-$		$(1.08\pm0.29)\times10^{-3}$	
Γ_{147}	$\phi\rho^0$		$(6\ \pm3\ )\times10^{-4}$	
Γ_{148}	$\phi\pi^+\pi^-$ 3-body		$(7\ \pm5\ )\times10^{-4}$	
Γ_{149}	$K^*(892)^0K^-\pi^+$ + c.c.	[f]	$< 8 \times10^{-4}$	CL=90%
Γ_{150}	$K^*(892)^0K^-\pi^+$			
Γ_{151}	$\overline{K}^*(892)^0K^+\pi^-$			
Γ_{152}	$K^*(892)^0\overline{K}^*(892)^0$		$(1.4\ \pm0.5\ )\times10^{-3}$	

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 2$ forbidden via mixing (*C2M*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) violating modes

Γ_{153}	$K^+\ell^-\overline{\nu}_\ell$ (via $\overline{D}^0$)	*C2M*		$< 1.7 \times10^{-4}$	CL=90%
Γ_{154}	$K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0$)	*C2M*		$< 1.0 \times10^{-3}$	CL=90%
Γ_{155}	$K^+\pi^-$	*DC*		$(2.8\ \pm0.9\ )\times10^{-4}$	
Γ_{156}	$K^+\pi^-$ (via $\overline{D}^0$)			$< 1.9 \times10^{-4}$	CL=90%
Γ_{157}	$K^+\pi^-\pi^+\pi^-$	*DC*		$(1.9\ \pm2.7\ )\times10^{-4}$	
Γ_{158}	$K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0$)			$< 4 \times10^{-4}$	CL=90%
Γ_{159}	μ^- anything (via $\overline{D}^0$)			$< 4 \times10^{-4}$	CL=90%
Γ_{160}	e^+e^-	*C1*		$< 1.3 \times10^{-5}$	CL=90%
Γ_{161}	$\mu^+\mu^-$	*C1*		$< 4.1 \times10^{-6}$	CL=90%
Γ_{162}	$\pi^0e^+e^-$	*C1*		$< 4.5 \times10^{-5}$	CL=90%
Γ_{163}	$\pi^0\mu^+\mu^-$	*C1*		$< 1.8 \times10^{-4}$	CL=90%
Γ_{164}	ηe^+e^-	*C1*		$< 1.1 \times10^{-4}$	CL=90%
Γ_{165}	$\eta\mu^+\mu^-$	*C1*		$< 5.3 \times10^{-4}$	CL=90%
Γ_{166}	$\rho^0e^+e^-$	*C1*		$< 1.0 \times10^{-4}$	CL=90%
Γ_{167}	$\rho^0\mu^+\mu^-$	*C1*		$< 2.3 \times10^{-4}$	CL=90%
Γ_{168}	ωe^+e^-	*C1*		$< 1.8 \times10^{-4}$	CL=90%
Γ_{169}	$\omega\mu^+\mu^-$	*C1*		$< 8.3 \times10^{-4}$	CL=90%
Γ_{170}	ϕe^+e^-	*C1*		$< 5.2 \times10^{-5}$	CL=90%
Γ_{171}	$\phi\mu^+\mu^-$	*C1*		$< 4.1 \times10^{-4}$	CL=90%
Γ_{172}	$\overline{K}^0e^+e^-$		[g]	$< 1.1 \times10^{-4}$	CL=90%
Γ_{173}	$\overline{K}^0\mu^+\mu^-$		[g]	$< 2.6 \times10^{-4}$	CL=90%
Γ_{174}	$\overline{K}^*(892)^0e^+e^-$		[g]	$< 1.4 \times10^{-4}$	CL=90%
Γ_{175}	$\overline{K}^*(892)^0\mu^+\mu^-$		[g]	$< 1.18 \times10^{-3}$	CL=90%
Γ_{176}	$\pi^+\pi^-\pi^0\mu^+\mu^-$	*C1*		$< 8.1 \times10^{-4}$	CL=90%
Γ_{177}	$\mu^\pm e^\mp$	*LF*	[h]	$< 1.9 \times10^{-5}$	CL=90%
Γ_{178}	$\pi^0e^\pm\mu^\mp$	*LF*	[h]	$< 8.6 \times10^{-5}$	CL=90%
Γ_{179}	$\eta e^\pm\mu^\mp$	*LF*	[h]	$< 1.0 \times10^{-4}$	CL=90%
Γ_{180}	$\rho^0e^\pm\mu^\mp$	*LF*	[h]	$< 4.9 \times10^{-5}$	CL=90%
Γ_{181}	$\omega e^\pm\mu^\mp$	*LF*	[h]	$< 1.2 \times10^{-4}$	CL=90%
Γ_{182}	$\phi e^\pm\mu^\mp$	*LF*	[h]	$< 3.4 \times10^{-5}$	CL=90%
Γ_{183}	$\overline{K}^0e^\pm\mu^\mp$	*LF*	[h]	$< 1.0 \times10^{-4}$	CL=90%
Γ_{184}	$\overline{K}^*(892)^0e^\pm\mu^\mp$	*LF*	[h]	$< 1.0 \times10^{-4}$	CL=90%

Γ_{185}	A dummy mode used by the fit.	$(16.9\ \pm3.5\ )$ %	S=1.1

[a] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \rightarrow$ (η anything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in these Particle Listings.

[b] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ here is really an e^+.

[c] The branching fraction for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[d] The two experiments measuring this fraction are in serious disagreement. See the Particle Listings.

[e] The experiments on the division of this charge mode amongst its submodes disagree, and the submode branching fractions here add up to considerably more than the charged-mode fraction.

[f] However, these upper limits are in serious disagreement with values obtained in another experiment.

[g] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

[h] The value is for the sum of the charge states of particle/antiparticle states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 51 branching ratios uses 122 measurements and one constraint to determine 28 parameters. The overall fit has a $\chi^2 = 64.8$ for 95 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_2	x_8	x_9	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{29}	x_{37}
x_8	6									
x_9	32	19								
x_{17}	1	24	5							
x_{18}	1	8	3	2						
x_{19}	13	46	42	11	6					
x_{20}	1	5	3	1	24	8				
x_{21}	1	6	4	2	36	10	66			
x_{29}	3	11	10	3	7	23	16	18		
x_{37}	3	12	11	3	2	26	3	3	6	
x_{46}	1	3	2	1	18	5	33	51	9	3
x_{55}	2	8	7	2	1	17	1	2	4	32
x_{64}	1	3	2	1	16	5	30	46	8	2
x_{68}	1	3	2	1	17	5	58	47	11	2
x_{71}	1	2	2	1	13	4	24	37	7	2
x_{74}	1	4	2	1	21	6	39	60	10	2
x_{80}	1	6	4	1	30	9	56	84	18	3
x_{81}	1	5	4	1	7	10	24	18	43	3
x_{83}	1	3	2	1	0	5	1	1	1	21
x_{87}	0	2	1	0	2	3	3	5	1	11
x_{98}	0	2	1	0	7	3	13	20	4	3
x_{106}	1	3	3	1	2	6	4	4	23	2
x_{117}	8	28	26	7	4	61	5	6	14	16
x_{118}	0	2	1	0	9	2	17	25	4	1
x_{119}	1	4	3	1	14	6	26	39	7	2
x_{123}	1	3	2	1	11	6	20	30	6	2
x_{140}	0	2	1	0	11	3	20	30	5	1
x_{185}	−28	−20	−23	−7	−34	−31	−53	−70	−50	−26

	x_{46}	x_{55}	x_{64}	x_{68}	x_{71}	x_{74}	x_{80}	x_{81}	x_{83}	x_{87}
x_{55}	1									
x_{64}	23	1								
x_{68}	24	1	21							
x_{71}	43	1	17	17						
x_{74}	30	1	7	28	22					
x_{80}	43	2	38	40	31	50				
x_{81}	9	2	8	14	7	11	17			
x_{83}	1	7	0	0	0	0	1	1		
x_{87}	9	4	2	2	4	3	4	1	2	
x_{98}	40	1	9	9	17	12	17	4	1	4
x_{106}	2	1	2	2	2	2	4	10	0	0
x_{117}	3	10	3	3	2	4	6	6	3	2
x_{118}	13	0	11	12	9	15	21	5	0	1
x_{119}	20	1	18	18	14	23	33	7	0	2
x_{123}	15	1	14	14	11	18	25	6	0	2
x_{140}	15	1	14	14	11	18	25	6	0	1
x_{185}	−68	−21	−33	−38	−45	−43	−64	−38	−14	−23

	x_{98}	x_{106}	x_{117}	x_{118}	x_{119}	x_{123}	x_{140}
x_{106}	1						
x_{117}	2	4					
x_{118}	5	1	2				
x_{119}	8	2	4	10			
x_{123}	6	1	3	8	12		
x_{140}	6	1	2	8	12	9	
x_{185}	−34	−25	−19	−18	−30	−24	−23

D^0 BRANCHING RATIOS

See the "Note on D Mesons" in the $D^{\pm}$ Listings.

Some older now obsolete results have been omitted from these Listings.

Inclusive modes

$\Gamma(e^+ \text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.0675±0.0029 OUR AVERAGE					
0.069 ±0.003 ±0.005	1670	ALBRECHT	96C	ARG	$e^+e^- \approx$ 10 GeV
0.0664±0.0018±0.0029	4609	[13] KUBOTA	96B	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.075 ±0.011 ±0.004	137	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.15 ±0.05		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.055 ±0.037	12	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

[13] KUBOTA 96B uses $D^{*+} \rightarrow D^0\pi^+$ (and charge conjugate) events in which the D^0 subsequently decays to $X e^+ \nu_e$.

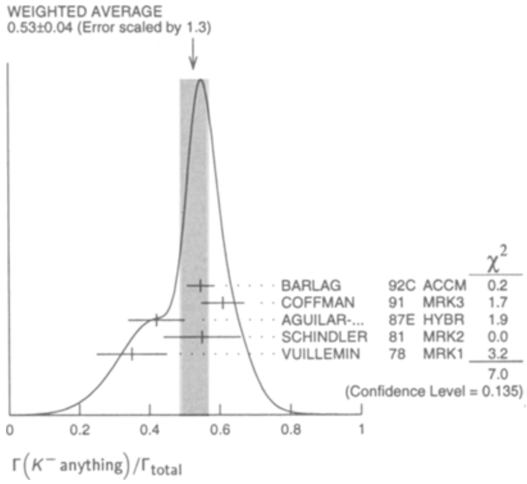
$\Gamma(\mu^+ \text{anything})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.066±0.008 OUR FIT					
0.060±0.007±0.012	310	ALBRECHT	96C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^- \text{anything})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.53 ±0.04 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
$0.546^{+0.039}_{-0.038}$		[14] BARLAG	92C	ACCM	π^- Cu 230 GeV
0.609±0.032±0.052		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.42 ±0.08		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.55 ±0.11	121	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.35 ±0.10	19	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

[14] BARLAG 92C computes the branching fraction using topological normalization.



$[\Gamma(\overline{K}^0 \text{anything}) + \Gamma(K^0 \text{anything})]/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.42 ±0.05 OUR AVERAGE					
0.455±0.050±0.032		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.29 ±0.11	13	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.57 ±0.26	6	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

$\Gamma(K^+ \text{anything})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.034^{+0.006}_{-0.004}$ OUR AVERAGE					
$0.034^{+0.007}_{-0.005}$		[15] BARLAG	92C	ACCM	π^- Cu 230 GeV
0.028±0.009±0.004		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.03^{+0.05}_{-0.02}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.08 ±0.03	25	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

[15] BARLAG 92C computes the branching fraction using topological normalization.

Semileptonic modes

$\Gamma(K^-\ell^+\nu_\ell)/\Gamma_{\rm total}$ Γ_7/Γ

We average our $K^- e^+ \nu_e$ and $K^- \mu^+ \nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.03 to be able to use it with the $K^- e^+ \nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID	COMMENT
0.0350±0.0017 OUR AVERAGE	Error includes scale factor of 1.3.	
0.0366±0.0018	PDG 98	Our $\Gamma(K^- e^+ \nu_e)/\Gamma_{\rm total}$
0.0333±0.0018	PDG 98	1.03 x our $\Gamma(K^- \mu^+ \nu_\mu)/\Gamma_{\rm total}$

$\Gamma(K^- e^+ \nu_e)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0366±0.0018 OUR FIT				
0.034 ±0.005 ±0.004	55	ADLER 89	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^- e^+ \nu_e)/\Gamma(K^-\pi^+)$ Γ_8/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.95 ±0.04 OUR FIT				
0.95 ±0.04 OUR AVERAGE				
0.978±0.027±0.044	2510	[16] BEAN 93C	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.90 ±0.06 ±0.06	584	[17] CRAWFORD 91B	CLEO	$e^+e^- \approx$ 10.5 GeV
0.91 ±0.07 ±0.11	250	[18] ANJOS 89F	E691	Photoproduction

[16] BEAN 93C uses $K^-\mu^+\nu_\mu$ as well as $K^- e^+ \nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events. A pole mass of 2.00 ± 0.12 ± 0.18 GeV/c^2 is obtained from the q^2 dependence of the decay rate.

[17] CRAWFORD 91B uses $K^- e^+ \nu_e$ and $K^-\mu^+\nu_\mu$ candidates to measure a pole mass of $2.1^{+0.4}_{-0.2}{}^{+0.3}_{-0.2}$ GeV/c^2 from the q^2 dependence of the decay rate.

[18] ANJOS 89F measures a pole mass of $2.1^{+0.4}_{-0.2} \pm 0.2$ GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(K^-\mu^+\nu_\mu)/\Gamma(K^-\pi^+)$ Γ_9/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.84 ±0.04 OUR FIT				
0.84 ±0.04 OUR AVERAGE				
0.852±0.034±0.028	1897	[19] FRABETTI 95G	E687	γ Be $\overline{E}_\gamma$= 220 GeV
0.82 ±0.13 ±0.13	338	[20] FRABETTI 93I	E687	γ Be $\overline{E}_\gamma$= 221 GeV
0.79 ±0.08 ±0.09	231	[21] CRAWFORD 91B	CLEO	$e^+e^- \approx$ 10.5 GeV

[19] FRABETTI 95G extracts the ratio of form factors $f_-(0)/f_+(0) = -1.3^{+3.6}_{-3.4} \pm 0.6$, and measures a pole mass of $1.87^{+0.11}_{-0.08}{}^{+0.07}_{-0.06}$ GeV/c^2 from the q^2 dependence of the decay rate.

[20] FRABETTI 93I measures a pole mass of $2.1^{+0.7}_{-0.3}{}^{+0.7}_{-0.3}$ GeV/c^2 from the q^2 dependence of the decay rate.

[21] CRAWFORD 91B measures a pole mass of 2.00 ± 0.12 ± 0.18 GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(K^-\mu^+\nu_\mu)/\Gamma(\mu^+ \text{anything})$ Γ_9/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.49 ±0.06 OUR FIT				
0.472±0.051±0.040	232	KODAMA 94	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.32 ±0.05 ±0.05	124	KODAMA 91	EMUL	pA 800 GeV

$\Gamma(K^-\pi^0 e^+\nu_e)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.016^{+0.013}_{-0.005}\pm0.002$	4	[22] BAI 91	MRK3	$e^+e^- \approx$ 3.77 GeV

[22] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892) e^+\nu_e$. BAI 91 uses 56 $K^- e^+ \nu_e$ events to measure a pole mass of 1.8 ± 0.3 ± 0.2 GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(\overline{K}^0\pi^- e^+\nu_e)/\Gamma_{\rm total}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.028^{+0.017}_{-0.008}\pm0.003$	6	[23] BAI 91	MRK3	$e^+e^- \approx$ 3.77 GeV

[23] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892) e^+\nu_e$.

$\Gamma(K^*(892)^- e^+\nu_e)/\Gamma(K^- e^+\nu_e)$ Γ_{18}/Γ_8

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.55±0.09 OUR FIT			
0.51±0.18±0.06	CRAWFORD 91B	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^- e^+\nu_e)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{18}/Γ_{21}

Unseen decay modes of the $\overline{K}^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.37±0.06 OUR FIT				
0.38±0.06±0.03	152	[24] BEAN 93C	CLE2	$e^+e^- \approx \Upsilon(4S)$

[24] BEAN 93C uses $K^{*-}\mu^+\nu_\mu$ as well as $K^{*-} e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(K^*(892)^-\ell^+\nu_\ell)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{13}/Γ_{21}

This an average of the $K^*(892)^- e^+\nu_e$ and $K^*(892)^-\mu^+\nu_\mu$ ratios. Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.07±0.06	137	[25] ALEXANDER 90B	CLEO	e^+e^- 10.5–11 GeV

[25] ALEXANDER 90B cannot exclude extra π^0's in the final state. See nearby data blocks for more detailed results.

$\Gamma(\overline{K}^*(892)^0\pi^- e^+\nu_e)/\Gamma(K^*(892)^- e^+\nu_e)$ Γ_{14}/Γ_{18}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.64	90	[26] CRAWFORD 91B	CLEO	$e^+e^- \approx$ 10.5 GeV

[26] The limit on $(\overline{K}^*(892)\pi)^-\ \mu^+\nu_\mu$ below is much stronger.

$\Gamma(K^-\pi^+\pi^-\mu^+\nu_\mu)/\Gamma(K^-\mu^+\nu_\mu)$ Γ_{15}/Γ_9

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.037	90	KODAMA 93B	E653	π^- emulsion 600 GeV

$\Gamma((\overline{K}^*(892)\pi)^-\mu^+\nu_\mu)/\Gamma(K^-\mu^+\nu_\mu)$ Γ_{16}/Γ_9

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.043	90	[27] KODAMA 93B	E653	π^- emulsion 600 GeV

[27] KODAMA 93B searched in $K^-\pi^+\pi^-\mu^+\nu_\mu$, but the limit includes other $(\overline{K}^*(892)\pi)^-$ charge states.

$\Gamma(\pi^- e^+\nu_e)/\Gamma_{\rm total}$ Γ_{17}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0037±0.0006 OUR FIT				
$0.0039^{+0.0023}_{-0.0011}\pm0.0004$	7	[28] ADLER 89	MRK3	e^+e^- 3.77 GeV

[28] This result of ADLER 89 gives $|\frac{V_{cd}}{V_{cs}} \cdot \frac{f_+^\pi(0)}{f_+^K(0)}|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$.

$\Gamma(\pi^- e^+\nu_e)/\Gamma(K^- e^+\nu_e)$ Γ_{17}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.102±0.017 OUR FIT				
0.101±0.018 OUR AVERAGE				
0.101±0.020±0.003	91	[29] FRABETTI 96B	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.103±0.039±0.013	87	[30] BUTLER 95	CLE2	< 0.156 (90% CL)

[29] FRABETTI 96B uses both e and μ events, and makes a small correction to the μ events to make them effectively e events. This result gives $|\frac{V_{cd}}{V_{cs}} \cdot \frac{f_+^\pi(0)}{f_+^K(0)}|^2 = 0.050 \pm 0.011 \pm 0.002$.

[30] BUTLER 95 has 87 ± 33 $\pi^- e^+\nu_e$ events. The result gives $|\frac{V_{cd}}{V_{cs}} \cdot \frac{f_+^\pi(0)}{f_+^K(0)}|^2 = 0.052 \pm 0.020 \pm 0.007$.

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

$\Gamma(K^-\pi^+)/\Gamma_{\rm total}$ Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0385±0.0009 OUR FIT				
0.0388±0.0009 OUR AVERAGE				
0.0381±0.0015±0.0016		[31] ARTUSO 98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.0390±0.0009±0.0012	5392	[31] BARATE 97C	ALEP	From Z decays
0.045 ±0.006 ±0.004		[32] ALBRECHT 94	ARG	$e^+e^- \approx \Upsilon(4S)$
0.0341±0.0012±0.0028	1173	[31] ALBRECHT 94F	ARG	$e^+e^- \approx \Upsilon(4S)$
0.0395±0.0008±0.0017	4208	[31,33] AKERIB 93	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.0362±0.0034±0.0044		[31] DECAMP 91J	ALEP	From Z decays
0.045 ±0.008 ±0.005	56	[31] ABACHI 88	HRS	e^+e^- 29 GeV
0.042 ±0.004 ±0.004	930	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.041 ±0.006	263	[34] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.043 ±0.010	130	[35] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[31] ABACHI 88, DECAMP 91J, AKERIB 93, ALBRECHT 94F, BARATE 97C, and ARTUSO 98 use $D^*(2010)^+ \rightarrow D^0\pi^+$ decays. The π^+ is both slow and of low p_T with respect to the event thrust axis or nearest jet ($\approx D^{*+}$ direction). The excess number of such π^+'s over background gives the number of $D^*(2010)^+ \rightarrow D^0\pi^+$ events, and the fraction with $D^0 \rightarrow K^-\pi^+$ gives the $D^0 \rightarrow K^-\pi^+$ branching fraction.

[32] ALBRECHT 94 uses D^0 mesons from $\overline{B}^0 \rightarrow D^{*+}\ell^-\overline{\nu}_\ell$ decays. This is a different set of events than used by ALBRECHT 94F.

[33] This AKERIB 93 value includes radiative corrections; without them the value is 0.0391 ± 0.0008 ± 0.0017.

[34] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \rightarrow \psi(3770))$ × branching fraction to be 0.24 ± 0.02 nb. We use the MARK-3 (ADLER 88C) value of σ = 5.8 ± 0.5 ± 0.6 nb.

[35] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \rightarrow \psi(3770))$ × branching fraction to be 0.25 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of σ = 5.8 ± 0.5 ± 0.6 nb.

$\Gamma(\overline{K}^0\pi^0)/\Gamma(K^-\pi^+)$ Γ_{20}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.55±0.06 OUR FIT	Error includes scale factor of 1.1.			
1.36±0.23±0.22	119	ANJOS 92B	E691	γ Be 80–240 GeV

$\Gamma(\overline{K}^0\pi^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{20}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.390±0.031 OUR FIT				
0.378±0.033 OUR AVERAGE				
0.44 ±0.02 ±0.05	1942	PROCARIO 93B	CLE2	e^+e^- 10.36–10.7 GeV
0.34 ±0.04 ±0.02	92	[36] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
0.36 ±0.04 ±0.08	104	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[36] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.054 ±0.004 OUR FIT	Error includes scale factor of 1.2.			
0.055 ±0.005 OUR AVERAGE				
0.0503±0.0039±0.0049	284	[37] ALBRECHT 94F	ARG	$e^+e^- \approx \Upsilon(4S)$
0.064 ±0.005 ±0.010		ADLER 87	MRK3	e^+e^- 3.77 GeV
0.052 ±0.016	32	[38] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.079 ±0.023	28	[39] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[37] See the footnote on the ALBRECHT 94F measurement of $\Gamma(K^-\pi^+)/\Gamma_{\text{total}}$ for the method used.

[38] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.30 ± 0.08 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

[39] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.46 ± 0.12 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma(K^-\pi^+)$ Γ_{21}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.41±0.10 OUR FIT	Error includes scale factor of 1.2.			
1.65±0.17 OUR AVERAGE				
1.61±0.10±0.15	856	FRABETTI 94J	E687	γBe $\overline{E}_\gamma$=220 GeV
1.7 ±0.8	35	AVERY 80	SPEC	$\gamma N \to D^{*+}$
2.8 ±1.0	116	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(\overline{K}^0\rho^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{22}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
0.223±0.027 OUR AVERAGE	Error includes scale factor of 1.2.		
0.350±0.028±0.067	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.227±0.032±0.009	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV
0.215±0.051±0.037	ANJOS 93	E691	γBe 90–260 GeV
0.20 ±0.06 ±0.03	FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.12 ±0.01 ±0.07	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 f_0(980))/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{73}/Γ_{21}

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.106±0.029 OUR AVERAGE			
0.131±0.031±0.034	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.088±0.035±0.012	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0 f_2(1270))/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{77}/Γ_{21}

Unseen decay modes of the $f_2(1270)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.076±0.028 OUR AVERAGE			
0.065±0.025±0.030	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.088±0.037±0.014	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0 f_0(1370))/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{79}/Γ_{21}

Unseen decay modes of the $f_0(1370)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.13 ±0.04 OUR AVERAGE			
0.123±0.035±0.049	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.131±0.045±0.021	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{80}/Γ_{21}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.93 ±0.04 OUR FIT	Error includes scale factor of 1.1.			
0.96 ±0.04 OUR AVERAGE				
0.938±0.054±0.038		FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
1.08 ±0.063±0.045		ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV
0.720±0.145±0.185		ANJOS 93	E691	γBe 90–260 GeV
0.96 ±0.12 ±0.075		FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.84 ±0.06 ±0.08		ADLER 87	MRK3	e^+e^- 3.77 GeV
$1.05\,{}^{+0.23}_{-0.26}\,{}^{+0.07}_{-0.09}$	25	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K_0^*(1430)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{102}/Γ_{21}

Unseen decay modes of the $\overline{K}_0^*(1430)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.19 ±0.06 OUR AVERAGE			
0.176±0.044±0.047	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.208±0.055±0.034	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K_2^*(1430)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{103}/Γ_{21}

Unseen decay modes of the $\overline{K}_2^*(1430)^-$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.15	90	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\text{ nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{28}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
0.27 ±0.04 OUR AVERAGE			
0.263±0.024±0.041	ANJOS 93	E691	γBe 90–260 GeV
0.26 ±0.08 ±0.05	FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.33 ±0.05 ±0.10	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_{29}/Γ

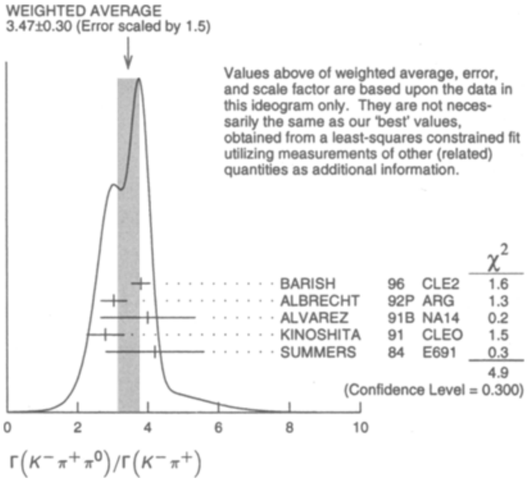
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.139±0.009 OUR FIT	Error includes scale factor of 1.3.			
0.131±0.016 OUR AVERAGE				
0.133±0.012±0.013	931	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.117±0.043	37	[40] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

[40] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.68 ± 0.23 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

$\Gamma(K^-\pi^+\pi^0)/\Gamma(K^-\pi^+)$ Γ_{29}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
3.62±0.23 OUR FIT	Error includes scale factor of 1.4.			
3.47±0.30 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.			
3.81±0.07±0.26	10k	BARISH 96	CLE2	$e^+e^- \approx \Upsilon(4S)$
3.04±0.16±0.34	931	[41] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
4.0 ±0.9 ±1.0	69	ALVAREZ 91B	NA14	Photoproduction
2.8 ±0.14±0.52	1050	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV
4.2 ±1.4	41	SUMMERS 84	E691	Photoproduction

[41] This value is calculated from numbers in Table 1 of ALBRECHT 92P.



$\Gamma(K^-\rho^+)/\Gamma(K^-\pi^+\pi^0)$ Γ_{30}/Γ_{29}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78 ±0.06 OUR AVERAGE				
0.765±0.041±0.054		FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.647±0.039±0.150		ANJOS 93	E691	γBe 90–260 GeV
0.81 ±0.03 ±0.06		ADLER 87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.31\,{}^{+0.20}_{-0.14}$	13	SUMMERS 84	E691	Photoproduction
$0.85\,{}^{+0.11}_{-0.15}\,{}^{+0.09}_{-0.10}$	31	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^*(892)^-\pi^+)/\Gamma(K^-\pi^+\pi^0)$ Γ_{80}/Γ_{29}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.363±0.035 OUR FIT	Error includes scale factor of 1.3.		
0.28 ±0.04 OUR AVERAGE			
0.444±0.084±0.147	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.252±0.033±0.035	ANJOS 93	E691	γBe 90–260 GeV
0.36 ±0.06 ±0.09	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma(K^-\pi^+\pi^0)$ Γ_{81}/Γ_{29}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.227±0.027 OUR FIT			
0.221±0.029 OUR AVERAGE			
0.248±0.047±0.023	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.213±0.027±0.035	ANJOS 93	E691	γBe 90–260 GeV
0.20 ±0.03 ±0.05	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0 \text{ nonresonant})/\Gamma(K^-\pi^+\pi^0)$ Γ_{33}/Γ_{29}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.049 ± 0.018 OUR AVERAGE Error includes scale factor of 1.1.					
$0.101\pm0.033\pm0.040$		FRABETTI	94G	E687	γBe, $\overline{E}_\gamma \approx 220$ GeV
$0.036\pm0.004\pm0.018$		ANJOS	93	E691	γBe 90–260 GeV
$0.09\ \pm0.02\ \pm0.04$		ADLER	87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.51\ \pm0.22$	21	SUMMERS	84	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma(\overline{K}^0\pi^0)$ Γ_{81}/Γ_{20}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.49 ± 0.23 OUR FIT Error includes scale factor of 1.1.					
$1.65^{+0.39}_{-0.31}\pm0.20$	122	PROCARIO	93B	CLE2	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(\overline{K}^*_2(1430)^0\pi^0)/\Gamma(\overline{K}^*(892)^0\pi^0)$ Γ_{104}/Γ_{81}

Unseen decay modes of the $\overline{K}^*_2(1430)^0$ and $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	PROCARIO	93B	CLE2	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(\overline{K}^0\pi^0\pi^0 \text{ nonresonant})/\Gamma(\overline{K}^0\pi^0)$ Γ_{36}/Γ_{20}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.37\pm0.08\pm0.04$	76	PROCARIO	93B	CLE2	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{37}/Γ

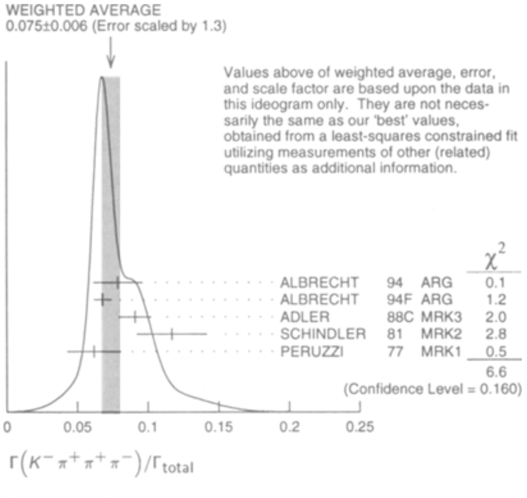
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.076\ \pm0.004$ OUR FIT Error includes scale factor of 1.1.					
$0.075\ \pm0.006$ OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
$0.079\ \pm0.015\ \pm0.009$		[42] ALBRECHT	94	ARG	$e^+e^- \approx \Upsilon(4S)$
$0.0680\pm0.0027\pm0.0057$	1430	[43] ALBRECHT	94F	ARG	$e^+e^- \approx \Upsilon(4S)$
$0.091\ \pm0.008\ \pm0.008$	992	ADLER	88C	MRK3	e^+e^- 3.77 GeV
$0.117\ \pm0.025$	185	[44] SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
$0.062\ \pm0.019$	44	[45] PERUZZI	77	MRK1	e^+e^- 3.77 GeV

[42] ALBRECHT 94 uses D^0 mesons from $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays. This is a different set of events than used by ALBRECHT 94F.

[43] See the footnote on the ALBRECHT 94F measurement of $\Gamma(K^-\pi^+)/\Gamma_{\text{total}}$ for the method used.

[44] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.68 ± 0.11 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

[45] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.36 ± 0.10 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.


WEIGHTED AVERAGE
0.075±0.006 (Error scaled by 1.3)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+)$ Γ_{37}/Γ_{19}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.96 ± 0.09 OUR FIT					
2.01 ± 0.13 OUR AVERAGE					
$1.7\ \pm0.2\ \pm0.2$	1745	ANJOS	92C	E691	γBe 90–260 GeV
$1.90\pm0.25\pm0.20$	337	ALVAREZ	91B	NA14	Photoproduction
$2.12\pm0.16\pm0.09$		BORTOLETTO	88	CLEO	e^+e^- 10.55 GeV
$2.0\ \pm0.9$	48	BAILEY	86	ACCM	π^- Be fixed target
$2.17\pm0.28\pm0.23$		ALBRECHT	85F	ARG	e^+e^- 10 GeV
$2.0\ \pm1.0$	10	BAILEY	83B	SPEC	π^- Be $\to D^0$
$2.2\ \pm0.8$	214	PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(K^-\pi^+\rho^0 \text{total})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{38}/Γ_{37}

This includes $K^-a_1(1260)^+$, $\overline{K}^*(892)^0\rho^0$, etc. The next entry gives the specifically 3-body fraction. We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	DOCUMENT ID		TECN	COMMENT
0.835 ± 0.035 OUR AVERAGE				
$0.80\ \pm0.03\ \pm0.05$	ANJOS	92C	E691	γBe 90–260 GeV
$0.855\pm0.032\pm0.030$	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.98\ \pm0.12\ \pm0.10$	ALVAREZ	91B	NA14	Photoproduction

$\Gamma(K^-\pi^+\rho^0 \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{39}/Γ_{37}

We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.063 ± 0.028 OUR AVERAGE					
$0.05\ \pm0.03\ \pm0.02$		ANJOS	92C	E691	γBe 90–260 GeV
$0.084\pm0.022\pm0.04$		COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.77\ \pm0.06\ \pm0.06$		[46] ALVAREZ	91B	NA14	Photoproduction
$0.85\ ^{+0.11}_{-0.22}$	180	PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV

[46] This value is for ρ^0 $(K^-\pi^+)$-nonresonant. ALVAREZ 91B cannot determine what fraction of this is $K^-a_1(1260)^+$.

$\Gamma(\overline{K}^*(892)^0\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{86}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included. We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.196\pm0.03\pm0.03$		ANJOS	92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.34\ \pm0.09\pm0.09$		ALVAREZ	91B	NA14	Photoproduction
$0.75\ \pm0.3$	5	BAILEY	83B	SPEC	πBe $\to D^0$
$0.15\ ^{+0.16}_{-0.15}$	20	PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{transverse})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{87}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.20\ \pm0.07$ OUR FIT				
$0.213\pm0.024\pm0.075$	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{ S-wave})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{88}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.375\pm0.045\pm0.06$	ANJOS	92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{ S-wave long.})/\Gamma_{\text{total}}$ Γ_{89}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{ P-wave})/\Gamma_{\text{total}}$ Γ_{90}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.009	90	ANJOS	92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{ D-wave})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{91}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.255\pm0.045\pm0.06$	ANJOS	92C	E691	γBe 90–260 GeV

$\Gamma(K^-\pi^+f_0(980))/\Gamma_{\text{total}}$ Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	ANJOS	92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0 f_0(980))/\Gamma_{\text{total}}$ Γ_{97}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ and $f_0(980)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	ANJOS	92C	E691	γBe 90–260 GeV

$\Gamma(K^-a_1(1260)^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{78}/Γ_{37}

Unseen decay modes of the $a_1(1260)^+$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
$0.97\ \pm0.14$ OUR AVERAGE				
$0.94\ \pm0.13\ \pm0.20$	ANJOS	92C	E691	γBe 90–260 GeV
$0.984\pm0.048\pm0.16$	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^- a_2(1320)^+)/\Gamma_{\rm total}$ Γ_{78}/Γ

Unseen decay modes of the $a_2(1320)^+$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.002	90	ANJOS 92C	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.006	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{98}/Γ_{37}

Unseen decay modes of the $K_1(1270)^-$ are included. The MARK3 and E691 experiments disagree considerably here.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.14 ±0.04 OUR FIT				
0.194±0.056±0.088		COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.013	90	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(K_1(1400)^-\pi^+)/\Gamma_{\rm total}$ Γ_{99}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.012	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(1410)^-\pi^+)/\Gamma_{\rm total}$ Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.012	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\,{\rm total})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{82}/Γ_{37}

This includes $\overline{K}^*(892)^0\rho^0$, *etc.* The next entry gives the specifically 3-body fraction. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.30±0.06±0.03	ANJOS 92C	E691	γBe 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\,\text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{83}/Γ_{37}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.19 ±0.04 OUR FIT			
0.18 ±0.04 OUR AVERAGE			
0.165±0.03 ±0.045	ANJOS 92C	E691	γBe 90–260 GeV
0.210±0.027±0.06	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^-\,{\rm nonresonant})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{45}/Γ_{37}

VALUE	DOCUMENT ID	TECN	COMMENT
0.233±0.032 OUR AVERAGE			
0.23 ±0.02 ±0.03	ANJOS 92C	E691	γBe 90–260 GeV
0.242±0.025±0.06	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_{46}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.100±0.012 OUR FIT				
0.103±0.022±0.025	140	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.134^{+0.032}_{-0.033}$		[47] BARLAG 92C	ACCM	π^- Cu 230 GeV

[47] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{46}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.84±0.20 OUR FIT				
1.86±0.23 OUR AVERAGE				
1.80±0.20±0.21	190	[48] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
2.8 ±0.8 ±0.8	46	ANJOS 92C	E691	γBe 90–260 GeV
1.85±0.26±0.30	158	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[48] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0\eta)/\Gamma(K^-\pi^+)$ Γ_{68}/Γ_{19}

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.64	90	ALBRECHT 89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\eta)/\Gamma(\overline{K}^0\pi^0)$ Γ_{68}/Γ_{20}

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.33±0.04 OUR FIT				
0.32±0.04±0.03	225	PROCARIO 93B	CLE2	$\eta \to \gamma\gamma$

$\Gamma(\overline{K}^0\eta)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{68}/Γ_{21}

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.130±0.017 OUR FIT				
0.14 ±0.02 ±0.02	80	PROCARIO 93B	CLE2	$\eta \to \pi^+\pi^-\pi^0$

$\Gamma(\overline{K}^0\omega)/\Gamma(K^-\pi^+)$ Γ_{71}/Γ_{19}

Unseen decay modes of the ω are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.54±0.09 OUR FIT			
1.00±0.36±0.20	ALBRECHT 89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{71}/Γ_{21}

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.38±0.07 OUR FIT				
0.33±0.09 OUR AVERAGE Error includes scale factor of 1.1.				
0.29±0.08±0.05	16	[49] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
0.54±0.14±0.16	40	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[49] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{71}/Γ_{46}

Unseen decay modes of the ω are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.21 ±0.04 OUR FIT			
0.220±0.048±0.0116	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\eta'(958))/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{72}/Γ_{21}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.32±0.04 OUR AVERAGE				
0.31±0.02±0.04	594	PROCARIO 93B	CLE2	$\eta' \to \eta\pi^+\pi^-, \rho^0\gamma$
0.37±0.13±0.06	18	[50] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV

[50] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(K^*(892)^-\rho^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{92}/Γ_{46}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.606±0.188±0.126	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+\,{\rm longitudinal})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{93}/Γ_{46}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.290±0.111	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+\,{\rm transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{94}/Γ_{46}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.317±0.180	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+\,P\text{-wave})/\Gamma_{\rm total}$ Γ_{95}/Γ

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	[51] COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

[51] Obtained using other $\overline{K}^*(892)\rho\,P$-wave limits and isospin relations.

$\Gamma(\overline{K}^*(892)^0\rho^0\,{\rm transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{87}/Γ_{46}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.15 ±0.06 OUR FIT			
0.126±0.111	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_1(1260)^0)/\Gamma_{\rm total}$ Γ_{76}/Γ

Unseen decay modes of the $a_1(1260)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.019	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{98}/Γ_{46}

Unseen decay modes of the $K_1(1270)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.106±0.028 OUR FIT			
0.10 ±0.03	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^0)/\Gamma_{\rm total}$ Γ_{100}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.037	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\,\text{3-body})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{83}/Γ_{46}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.14 ±0.04 OUR FIT Error includes scale factor of 1.1.			
0.191±0.106	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0\,{\rm nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{53}/Γ_{46}

VALUE	DOCUMENT ID	TECN	COMMENT
0.210±0.147±0.150	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_{54}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.149±0.037±0.030	24	[52] ADLER 88C	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.177±0.029		[53] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.209^{+0.074}_{-0.043}\pm0.012$	9	[53] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[52] ADLER 88C uses an absolute normalization method finding this decay channel opposite a detected $\overline{D}^0 \to K^+\pi^-$ in pure $D\overline{D}$ events.

[53] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction using topological normalization. They do not distinguish the presence of a third π^0, and thus are not included in the average.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+)$ — Γ_{55}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.05±0.10 OUR FIT				
0.98±0.11±0.11	225	[54] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV

[54] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{55}/Γ_{37}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.54±0.05 OUR FIT				
0.56±0.07 OUR AVERAGE				
$0.55\pm0.07^{+0.12}_{-0.09}$	167	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV
0.57±0.06±0.05	180	ANJOS 90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{105}/Γ_{55}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.45±0.15±0.15	ANJOS 90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{106}/Γ_{19}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.49±0.12 OUR FIT				
$\mathbf{0.58\pm0.19^{+0.24}_{-0.28}}$	46	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{106}/Γ_{29}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.134±0.034 OUR FIT				
0.13 ±0.02 ±0.03	214	PROCARIO 93B	CLE2	$\overline{K}^{*0}\eta \to K^-\pi^+/\gamma\gamma$

$\Gamma(K^-\pi^+\omega)/\Gamma(K^-\pi^+)$ — Γ_{107}/Γ_{19}

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78±0.12±0.10	99	[55] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV

[55] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^*(892)^0\omega)/\Gamma(K^-\pi^+)$ — Γ_{108}/Γ_{19}

Unseen decay modes of the $\overline{K}^*(892)^0$ and ω are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.28±0.11±0.04	17	[56] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV

[56] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^*(892)^0\omega)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{108}/Γ_{55}

Unseen decay modes of the $\overline{K}^*(892)^0$ and ω are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.44	90	[57] ANJOS 90D	E691	Photoproduction

[57] Recovered from the published limit, $\Gamma(\overline{K}^*(892)^0\omega)/\Gamma_{\text{total}}$, in order to make our normalization consistent.

$\Gamma(K^-\pi^+\eta'(958))/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{109}/Γ_{37}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.093±0.014±0.019	286	PROCARIO 93B	CLE2	$\eta' \to \eta\pi^+\pi^-,\ \rho^0\gamma$

$\Gamma(\overline{K}^*(892)^0\eta'(958))/\Gamma(K^-\pi^+\eta'(958))$ — $\Gamma_{110}/\Gamma_{109}$

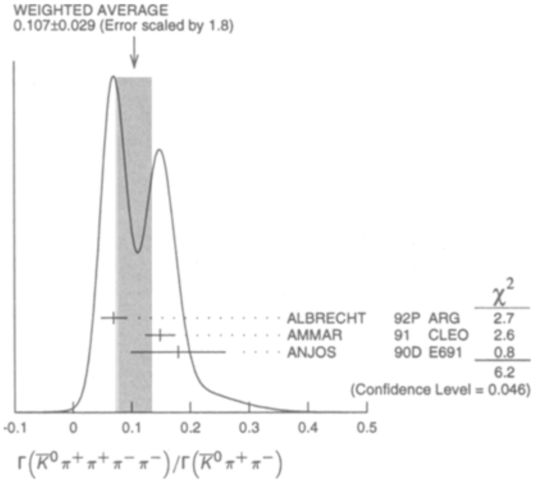
Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN
<0.15	90	PROCARIO 93B	CLE2

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{60}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.107±0.029 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.		
0.07 ±0.02 ±0.01	11	[58] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
0.149±0.026	56	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.18 ±0.07 ±0.04	6	ANJOS 90D	E691	Photoproduction

[58] This value is calculated from numbers in Table 1 of ALBRECHT 92P.



$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0))/\Gamma_{\text{total}}$ — Γ_{61}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.106^{+0.073}_{-0.029}\pm0.006}$	4	[59] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[59] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization, and does not distinguish the presence of a third π^0.

$\Gamma(\overline{K}^0K^+K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{62}/\Gamma_{21} = (\Gamma_{64}+\frac{1}{2}\Gamma_{74})/\Gamma_{21}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.172±0.014 OUR FIT				
0.178±0.019 OUR AVERAGE				
0.20 ±0.05 ±0.04	47	FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.170±0.022	136	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.24 ±0.08		BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
0.185±0.055	52	ALBRECHT 85B	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\phi)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{74}/Γ_{21}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.158±0.016 OUR FIT				
0.156±0.017 OUR AVERAGE				
0.13 ±0.06 ±0.02	13	FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.163±0.023	63	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.155±0.033	56	ALBRECHT 87E	ARG	e^+e^- 10 GeV
0.14 ±0.05	29	BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.186±0.052	26	ALBRECHT 85B	ARG	See ALBRECHT 87E

$\Gamma(\overline{K}^0K^+K^-\text{ non-}\phi)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{64}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.093±0.014 OUR FIT				
0.088±0.019 OUR AVERAGE				
0.11 ±0.04 ±0.03	20	FRABETTI 92B	E687	γBe $\overline{E}_\gamma$= 221 GeV
0.084±0.020		ALBRECHT 87E	ARG	e^+e^- 10 GeV

$\Gamma(K^0_SK^0_SK^0_S)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{65}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0154±0.0025 OUR AVERAGE				
0.0139±0.0019±0.0024	61	ASNER 96B	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.035 ±0.012 ±0.006	10	FRABETTI 94J	E687	γBe $\overline{E}_\gamma$=220 GeV
0.016 ±0.005	22	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.017 ±0.007 ±0.005	5	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+K^-K^-\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{66}/Γ_{37}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0028±0.0007±0.0001	20	FRABETTI 95C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+K^-\overline{K}^0\pi^0)/\Gamma_{\text{total}}$ — Γ_{67}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0072^{+0.0048}_{-0.0035}}$	[60] BARLAG 92C	ACCM	π^- Cu 230 GeV

[60] BARLAG 92C computes the branching fraction using topological normalization.

Pionic modes

$\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{111}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0397±0.0021 OUR AVERAGE				
0.040 ±0.002 ±0.003	2043	AITALA 98C	E791	π^- nucleus, 500 GeV
0.043 ±0.007 ±0.003	177	FRABETTI 94C	E687	γBe $\overline{E}_\gamma$= 220 GeV
0.0348±0.0030±0.0023	227	SELEN 93	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.048 ±0.013 ±0.008	51	ADAMOVICH 92	OMEG	π^- 340 GeV
0.055 ±0.008 ±0.005	120	ANJOS 91D	E691	Photoproduction
0.040 ±0.007 ±0.006	57	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.050 ±0.007 ±0.005	110	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.033 ±0.010 ±0.006	39	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.033 ±0.015		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

$\Gamma(\pi^0\pi^0)/\Gamma(K^-\pi^+)$ — Γ_{112}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.022±0.004±0.004	40	SELEN 93	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{113}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.016 ±0.011 OUR AVERAGE		Error includes scale factor of 2.7.		
$0.0390^{+0.0100}_{-0.0095}$		[61] BARLAG 92C	ACCM	π^- Cu 230 GeV
0.011 ±0.004 ±0.002	10	[62] BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV

[61] BARLAG 92C computes the branching fraction using topological normalization. Possible contamination by extra π^0's may partly explain the unexpectedly large value.

[62] All the BALTRUSAITIS 85E events are consistent with $\rho^0\pi^0$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{114}/Γ_{37}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.098±0.006 OUR AVERAGE				
0.095±0.007±0.002	814	FRABETTI 95C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
0.115±0.023±0.016	64	ADAMOVICH 92	OMEG	π^- 340 GeV
0.108±0.024±0.008	79	FRABETTI 92	E687	γBe
0.102±0.013	345	[63] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.096±0.018±0.007	66	ANJOS 91	E691	γBe 80–240 GeV

[63] AMMAR 91 finds 1.25 ± 0.25 ± 0.25 ρ^0's per $\pi^+\pi^+\pi^-\pi^-$ decay, but can't untangle the resonant substructure ($\rho^0\rho^0$, $a_1^\pm\pi^\mp$, $\rho^0\pi^+\pi^-$).

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{115}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.0192^{+0.0041}_{-0.0038}$	[64] BARLAG 92C	ACCM	π^- Cu 230 GeV

[64] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{\text{total}}$ — Γ_{116}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0004±0.0003	[65] BARLAG 92C	ACCM	π^- Cu 230 GeV

[65] BARLAG 92C computes the branching fraction using topological normalization.

Hadronic modes with a $K\overline{K}$ pair

$\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{117}/Γ_{19}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1109±0.0033 OUR FIT				
0.1109±0.0033 OUR AVERAGE				
0.109 ±0.003 ±0.003	3317	AITALA 98C	E791	π^- nucleus, 500 GeV
0.116 ±0.007 ±0.007	1102	ASNER 96B	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.109 ±0.007 ±0.009	581	FRABETTI 94C	E687	γBe $\overline{E}_\gamma$= 220 GeV
0.107 ±0.029 ±0.015	103	ADAMOVICH 92	OMEG	π^- 340 GeV
0.138 ±0.027 ±0.010	155	FRABETTI 92	E687	γBe
0.16 ±0.05	34	ALVAREZ 91B	NA14	Photoproduction
0.107 ±0.010 ±0.009	193	ANJOS 91D	E691	Photoproduction
0.10 ±0.02 ±0.01	131	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.117 ±0.010 ±0.007	249	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.122 ±0.018 ±0.012	118	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.113 ±0.030		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

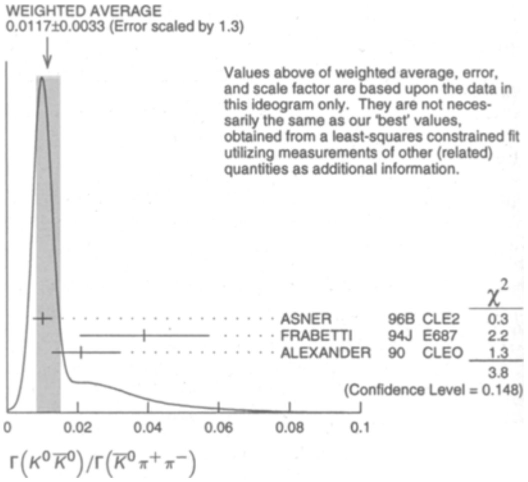
$\Gamma(K^+K^-)/\Gamma(\pi^+\pi^-)$ — $\Gamma_{117}/\Gamma_{111}$

The unused results here are redundant with $\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ and $\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ measurements by the same experiments.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.75±0.15±0.16	AITALA 98C	E791	π^- nucleus, 500 GeV
2.53±0.46±0.19	FRABETTI 94C	E687	γBe $\overline{E}_\gamma$= 220 GeV
2.23±0.81±0.46	ADAMOVICH 92	OMEG	π^- 340 GeV
1.95±0.34±0.22	ANJOS 91D	E691	Photoproduction
2.5 ±0.7	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
2.35±0.37±0.28	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV

$\Gamma(K^0\overline{K}^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{118}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0120±0.0033 OUR FIT		Error includes scale factor of 1.3.		
0.0117±0.0033 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
0.0101±0.0022±0.0016	26	ASNER 96B	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.039 ±0.013 ±0.013	20	FRABETTI 94J	E687	γBe $\overline{E}_\gamma$=220 GeV
$0.021^{+0.011}_{-0.008}$ ±0.002	5	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV



$\Gamma(K^0\overline{K}^0)/\Gamma(K^+K^-)$ — $\Gamma_{118}/\Gamma_{117}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.15±0.04 OUR FIT		Error includes scale factor of 1.2.		
0.24±0.16	4	[66] CUMALAT 88	SPEC	nN 0–800 GeV

[66] Includes a correction communicated to us by the authors of CUMALAT 88.

$\Gamma(K^0K^-\pi^+)/\Gamma(K^-\pi^+)$ — Γ_{119}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.167±0.026 OUR FIT	Error includes scale factor of 1.1.		
0.16 ±0.06	[67] ANJOS 91	E691	γBe 80–240 GeV

[67] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^0K^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{119}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.118±0.018 OUR FIT		Error includes scale factor of 1.1.		
0.119±0.021 OUR AVERAGE		Error includes scale factor of 1.3.		
0.108±0.019	61	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.16 ±0.03 ±0.02	39	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^*(892)^0K^0)/\Gamma(K^-\pi^+)$ — Γ_{139}/Γ_{19}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.03}_{-0.00}$	[68] ANJOS 91	E691	γBe 80–240 GeV

[68] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^*(892)^0K^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{139}/Γ_{21}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.029	90	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	90	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{140}/Γ_{19}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.090±0.020 OUR FIT			
$0.16^{+0.08}_{-0.06}$	[69] ANJOS 91	E691	γBe 80–240 GeV

[69] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^+K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{140}/Γ_{21}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.064±0.014 OUR FIT		Error includes scale factor of 1.1.		
0.058±0.014 OUR AVERAGE				
0.064±0.018	23	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.05 ±0.02 ±0.01	15	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^0 K^- \pi^+ \text{ nonresonant})/\Gamma(K^- \pi^+)$ Γ_{122}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.06±0.06	[70] ANJOS 91	E691	γ Be 80–240 GeV

[70] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0 K^+ \pi^-)/\Gamma(K^- \pi^+)$ Γ_{123}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
0.129±0.025 OUR FIT			
0.10 ±0.05	[71] ANJOS 91	E691	γ Be 80–240 GeV

[71] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0 K^+ \pi^-)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{123}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.091±0.018 OUR FIT				
0.098±0.020	55	AMMAR 91	CLEO	$e^+ e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^0 \overline{K}^0)/\Gamma(K^- \pi^+)$ Γ_{141}/Γ_{19}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.04}_{-0.00}$	[72] ANJOS 91	E691	γ Be 80–240 GeV

[72] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^0 \overline{K}^0)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{141}/Γ_{21}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	AMMAR 91	CLEO	$e^+ e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^- K^+)/\Gamma(K^- \pi^+)$ Γ_{142}/Γ_{19}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.03}_{-0.00}$	[73] ANJOS 91	E691	γ Be 80–240 GeV

[73] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^- K^+)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{142}/Γ_{21}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034±0.019	12	AMMAR 91	CLEO	$e^+ e^- \approx$ 10.5 GeV

$\Gamma(\overline{K}^0 K^+ \pi^- \text{ nonresonant})/\Gamma(K^- \pi^+)$ Γ_{126}/Γ_{19}

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.10^{+0.06}_{-0.05}}$	[74] ANJOS 91	E691	γ Be 80–240 GeV

[74] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^+ K^- \pi^0)/\Gamma(K^- \pi^+ \pi^0)$ Γ_{127}/Γ_{29}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0095±0.0026	151	ASNER 96B	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(K^0_S K^0_S \pi^0)/\Gamma_{\text{total}}$ Γ_{128}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
<0.00059	ASNER 96B	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\phi \pi^0)/\Gamma_{\text{total}}$ Γ_{143}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0014	90	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV

$\Gamma(\phi \eta)/\Gamma_{\text{total}}$ Γ_{144}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0028	90	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV

$\Gamma(\phi \omega)/\Gamma_{\text{total}}$ Γ_{145}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0021	90	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV

$\Gamma(K^+ K^- \pi^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{129}/Γ_{37}

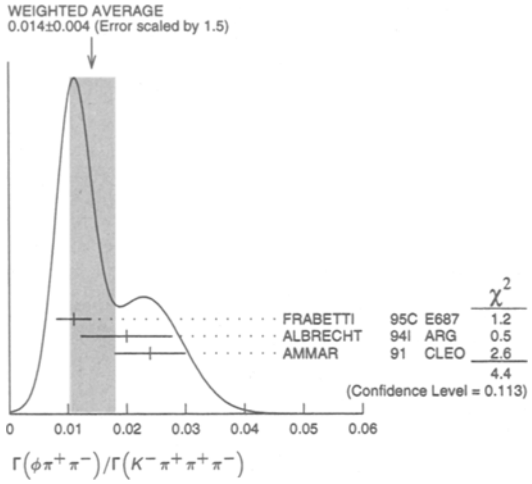
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0334±0.0028 OUR AVERAGE				
0.0313±0.0037±0.0036	136	AITALA 98D	E791	π^- nucleus, 500 GeV
0.035 ±0.004 ±0.002	244	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.041 ±0.007 ±0.005	114	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV
0.0314±0.010	89	AMMAR 91	CLEO	$e^+ e^- \approx$ 10.5 GeV
$0.028^{+0.008}_{-0.007}$		ANJOS 91	E691	γ Be 80–240 GeV

$\Gamma(\phi \pi^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{146}/Γ_{37}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.014 ±0.004 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.		
0.011 ±0.003		FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.020 ±0.006 ±0.005	28	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV
0.024 ±0.006	34	[75] AMMAR 91	CLEO	$e^+ e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0076^{+0.0066}_{-0.0049}$	3	ANJOS 91	E691	γ Be 80–240 GeV

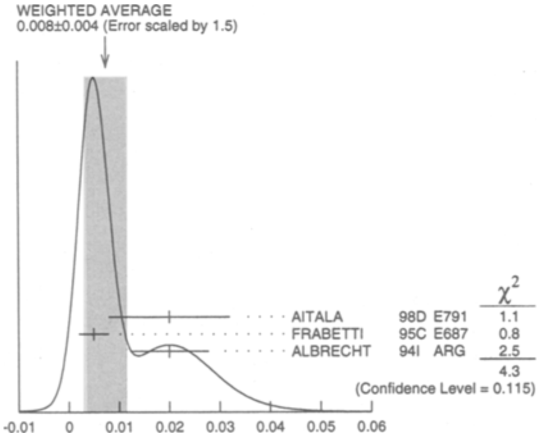
[75] AMMAR 91 measures $\phi \rho^0$, but notes that $\phi \rho^0$ dominates $\phi \pi^+ \pi^-$. We put the measurement here to keep from having more $\phi \rho^0$ than $\phi \pi^+ \pi^-$.



$\Gamma(\phi \rho^0)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{147}/Γ_{37}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.008±0.004 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.		
0.02 ±0.009±0.008		AITALA 98D	E791	π^- nucleus, 500 GeV
0.005±0.003		FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.020±0.006±0.005	28	ALBRECHT 94I	ARG	$e^+ e^- \approx$ 10 GeV



$\Gamma(\phi \pi^+ \pi^- \text{ 3-body})/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{148}/Γ_{37}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.009±0.004±0.006		AITALA 98D	E791	π^- nucleus, 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.006	90	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+ K^- \rho^0 \text{ 3-body})/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{132}/Γ_{37}

VALUE	DOCUMENT ID	TECN	COMMENT
0.012 ±0.003	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^*(892)^0 K^- \pi^+ + \text{c.c.})/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{149}/Γ_{37}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	[76] AITALA	98D	E791	π^- nucleus, 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.017	90	[76] FRABETTI	95C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
$0.010^{+0.016}_{-0.010}$		ANJOS	91	E691	γBe 80–240 GeV

[76] These upper limits are in conflict with values in the next two data blocks.

$\Gamma(K^*(892)^0 K^- \pi^+)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{150}/Γ_{37}

The $K^{*0} K^- \pi^+$ and $\overline{K}^{*0} K^+ \pi^-$ modes are distinguished by the charge of the pion in $D^*(2010)^\pm \rightarrow D^0 \pi^\pm$ decays. Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.043±0.014±0.009	55	[77] ALBRECHT	94I	ARG	$e^+e^- \approx$ 10 GeV

[77] This ALBRECHT 94I value is in conflict with upper limits given above.

$\Gamma(\overline{K}^*(892)^0 K^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{151}/Γ_{37}

The $K^{*0} K^- \pi^+$ and $\overline{K}^{*0} K^+ \pi^-$ modes are distinguished by the charge of the pion in $D^*(2010)^\pm \rightarrow D^0 \pi^\pm$ decays. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.023±0.013±0.009	30	[78] ALBRECHT	94I	ARG	$e^+e^- \approx$ 10 GeV

[78] This ALBRECHT 94I value is in conflict with upper limits given above.

$\Gamma(K^*(892)^0 \overline{K}^*(892)^0)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{152}/Γ_{37}

Unseen decay modes of the $K^*(892)^0$ and $\overline{K}^*(892)^0$ are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.018±0.007 OUR AVERAGE	Error includes scale factor of 1.2.					
0.016±0.006			FRABETTI	95C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
$0.036^{+0.020}_{-0.016}$		11	ANJOS	91	E691	γBe 80–240 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.02	90		AITALA	98D	E791	π^- nucleus, 500 GeV
<0.033	90		[79] AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

[79] A corrected value (G. Moneti, private communication).

$\Gamma(K^+ K^- \pi^+ \pi^- \text{non-}\phi)/\Gamma_{\text{total}}$ Γ_{135}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0017±0.0005	[80] BARLAG	92C	ACCM	π^- Cu 230 GeV

[80] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^+ K^- \pi^+ \pi^- \text{nonresonant})/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{136}/Γ_{37}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	FRABETTI	95C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.001^{+0.011}_{-0.001}$		ANJOS	91	E691	γBe 80–240 GeV

$\Gamma(K^0 \overline{K}^0 \pi^+ \pi^-)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{137}/Γ_{21}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.126±0.038±0.030	25	ALBRECHT	94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+ K^- \pi^+ \pi^- \pi^0)/\Gamma_{\text{total}}$ Γ_{138}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0031±0.0020	[81] BARLAG	92C	ACCM	π^- Cu 230 GeV

[81] BARLAG 92C computes the branching fraction using topological normalization.

Rare or forbidden modes

$\Gamma(K^+ \ell^- \overline{\nu}_\ell (\text{via } \overline{D}^0))/\Gamma(K^- \ell^+ \nu_\ell)$ Γ_{153}/Γ_7

This is a D^0-$\overline{D}^0$ mixing limit without the complications of possible doubly-Cabibbo-suppressed decays that occur when using hadronic modes. For the limits on $|m_{D^0_1} - m_{D^0_2}|$ and $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma_{D^0}$ that come from the best mixing limit, see near the beginning of these D^0 Listings.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.005	90	[82] AITALA	96C	E791	π^- nucleus, 500 GeV

[82] AITALA 96C uses $D^{*+} \rightarrow D^0 \pi^+$ (and charge conjugate) decays to identify the charm at production and $D^0 \rightarrow K^- \ell^+ \nu_\ell$ (and charge conjugate) decays to identify the charm at decay.

$\Gamma(K^+ \pi^- \text{ or } K^+ \pi^- \pi^+ \pi^- (\text{via } \overline{D}^0))/\Gamma(K^- \pi^+ \text{ or } K^- \pi^+ \pi^+ \pi^-)$ Γ_{154}/Γ_0

This is a D^0-$\overline{D}^0$ mixing limit. For the limits on $|m_{D^0_1} - m_{D^0_2}|$ and $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma_{D^0}$ that come from the best mixing limit, see near the beginning of these D^0 Listings.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0085	90	[83] AITALA	98	E791	π^- nucleus, 500 GeV

[83] AITALA 98 uses decay-time information to distinguish doubly Cabibbo-suppressed decays from D^0-$\overline{D}^0$ mixing. The fit allows interference between the two amplitudes, and also allows CP violation in this term. The central value obtained is $0.0039^{+0.0036}_{-0.0032} \pm 0.0016$. When interference is disallowed, the result becomes 0.0021 ± 0.0009 ± 0.0002.

$\Gamma(K^+ \pi^-)/\Gamma(K^- \pi^+)$ Γ_{155}/Γ_{19}

The $D^0 \rightarrow K^+ \pi^-$ mode is doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0072±0.0025 OUR AVERAGE						
$0.0068^{+0.0034}_{-0.0033} \pm 0.0007$			[84] AITALA	98	E791	π^- nucleus, 500 GeV
0.0077±0.0025±0.0025		19	[85] CINABRO	94	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.011	90		[85] AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.015	90	1 ± 6	[86] ANJOS	88C	E691	Photoproduction
<0.014	90		[87] ALBRECHT	87K	ARG	e^+e^- 10 GeV
<0.04	90		[87] ABACHI	86D	HRS	e^+e^- 29 GeV
<0.07	90	0	[88] BAILEY	86	ACCM	π^- Be fixed target
<0.11	90	2	[87] ALBRECHT	85F	ARG	e^+e^- 10 GeV
<0.081	90		[87,89] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
<0.23	90		[87,89] ALTHOFF	84B	TASS	e^+e^- 34.4 GeV
<0.11	90		[87,89] AVERY	80	SPEC	$\gamma N \rightarrow D^{*+}$
<0.16	90		[87,89] FELDMAN	77B	MRK1	e^+e^- 4 GeV
<0.18	90		[87,89] GOLDHABER	77	MRK1	e^+e^- 4 GeV

[84] AITALA 98 uses the charge of the pion in $D^{*\pm} \rightarrow (D^0 \text{ or } \overline{D}^0)\,\pi^\pm$ to tell whether a D^0 or a $\overline{D}^0$ was born. This result assumes no D^0-$\overline{D}^0$ mixing; it becomes $0.0090^{+0.0120}_{-0.0109} \pm 0.0044$ when mixing is allowed and decay-time information is used to distinguish doubly Cabibbo-suppressed decays from mixing.

[85] These experiments cannot distinguish between doubly Cabibbo-suppressed decay and D^0-$\overline{D}^0$ mixing.

[86] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.049.

[87] In these measurements, the charge of the pion in $D^{*\pm} \rightarrow (D^0 \text{ or } \overline{D}^0)\pi^\pm$ is used to tell whether a D^0 or a $\overline{D}^0$ was born. None of the measurements can distinguish between double Cabibbo suppression and mixing for the decay.

[88] BAILEY 86 searches for events with an oppositely charged eK pair. The limit is actually for $\Gamma(D^0 \rightarrow K^+ \pi^- \text{ or } K^+ \pi^- \pi^+ \pi^-)/\Gamma(D^0 \rightarrow K^- \pi^+ \text{ or } K^- \pi^+ \pi^+ \pi^-)$.

[89] The results are given as $\Gamma(K^+ \pi^-)/[\Gamma(K^- \pi^+)+\Gamma(K^+ \pi^-)]$ but do not change significantly for our denominator.

$\Gamma(K^+ \pi^- (\text{via } \overline{D}^0))/\Gamma(K^- \pi^+)$ Γ_{156}/Γ_{19}

This is a D^0-$\overline{D}^0$ mixing limit. For the limits on $|m_{D^0_1} - m_{D^0_2}|$ and $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma_{D^0}$ that come from the best mixing limit, see near the beginning of these D^0 Listings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.005	90	1 ± 4	[90] ANJOS	88C	E691	Photoproduction

[90] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.019. Combined with results on $K^\pm \pi^\mp \pi^+ \pi^-$, the limit is, assuming no interference, 0.0037.

$\Gamma(K^+ \pi^- \pi^+ \pi^-)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{157}/Γ_{37}

Doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.0025^{+0.0036}_{-0.0034} \pm 0.0003}$			[91] AITALA	98	E791	π^- nucleus, 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.018	90		[92] AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.018	90	5 ± 12	[93] ANJOS	88C	E691	Photoproduction

[91] AITALA 98 uses the charge of the pion in $D^{*\pm} \rightarrow (D^0 \text{ or } \overline{D}^0)\,\pi^\pm$ to tell whether a D^0 or a $\overline{D}^0$ was born. This result assumes no D^0-$\overline{D}^0$ mixing; it becomes $-0.0020^{+0.0117}_{-0.0106} \pm 0.0035$ when mixing is allowed and decay-time information is used to distinguish doubly Cabibbo-suppressed decays from mixing.

[92] AMMAR 91 cannot distinguish between doubly Cabibbo-suppressed decay and D^0-$\overline{D}^0$ mixing.

[93] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.033.

$\Gamma(K^+ \pi^- \pi^+ \pi^- (\text{via } \overline{D}^0))/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ Γ_{158}/Γ_{37}

This is a D^0-$\overline{D}^0$ mixing limit. For the limits on $|m_{D^0_1} - m_{D^0_2}|$ and $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma_{D^0}$ that come from the best mixing limit, see near the beginning of these D^0 Listings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.005	90	0 ± 4	[94] ANJOS	88C	E691	Photoproduction

[94] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.007. Combined with results on $K^\pm \pi^\mp$, the limit is, assuming no interference, 0.0037.

$\Gamma(\mu^- \text{anything} (\text{via } \overline{D}^0))/\Gamma(\mu^+ \text{anything})$ Γ_{159}/Γ_2

This is a D^0-$\overline{D}^0$ mixing limit. See the somewhat better limits above.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0056	90	LOUIS	86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.012	90	BENVENUTI	85	CNTR	μC, 200 GeV
<0.044	90	BODEK	82	SPEC	π^-, pFe $\rightarrow D^0$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{160}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.3 \times 10^{-5}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.3 \times 10^{-4}$	90		ADLER	88	MRK3	e^+e^- 3.77 GeV
$<1.7 \times 10^{-4}$	90	7	ALBRECHT	88G	ARG	e^+e^- 10 GeV
$<2.2 \times 10^{-4}$	90	8	HAAS	88	CLEO	e^+e^- 10 GeV

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{161}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<4.1 \times 10^{-6}$	90		ADAMOVICH	97	BEAT	π^- Cu, W 350 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4.2 \times 10^{-6}$	90		ALEXOPOU...	96	E771	p Si, 800 GeV
$<3.4 \times 10^{-5}$	90	1	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
$<7.6 \times 10^{-6}$	90	0	ADAMOVICH	95	BEAT	See ADAMOVICH 97
$<4.4 \times 10^{-5}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
$<3.1 \times 10^{-5}$	90		[95] MISHRA	94	E789	-4.1 ± 4.8 events
$<7.0 \times 10^{-5}$	90	3	ALBRECHT	88G	ARG	e^+e^- 10 GeV
$<1.1 \times 10^{-5}$	90		LOUIS	86	SPEC	π^- W 225 GeV
$<3.4 \times 10^{-4}$	90		AUBERT	85	EMC	Deep inelast. $\mu^- N$

[95] Here MISHRA 94 uses "the statistical approach advocated by the PDG." For an alternate approach, giving a limit of 9×10^{-6} at 90% confidence level, see the paper.

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_{162}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<4.5 \times 10^{-5}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^0 \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{163}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.8 \times 10^{-4}$	90	2	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<5.4 \times 10^{-4}$	90	3	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta e^+e^-)/\Gamma_{\text{total}}$ Γ_{164}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.1 \times 10^{-4}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{165}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5.3 \times 10^{-4}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\rho^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_{166}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.0 \times 10^{-4}$	90	2	[96] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4.5 \times 10^{-4}$	90	2	HAAS	88	CLEO	e^+e^- 10 GeV

[96] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 1.8 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\rho^0 \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{167}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<2.3 \times 10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4.9 \times 10^{-4}$	90	1	[97] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
$<8.1 \times 10^{-4}$	90	5	HAAS	88	CLEO	e^+e^- 10 GeV

[97] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 4.5 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\omega e^+e^-)/\Gamma_{\text{total}}$ Γ_{168}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.8 \times 10^{-4}$	90	1	[98] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[98] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.7 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\omega \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{169}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8.3 \times 10^{-4}$	90	0	[99] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[99] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 6.5 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\phi e^+e^-)/\Gamma_{\text{total}}$ Γ_{170}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5.2 \times 10^{-5}$	90	2	[100] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[100] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 7.6 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\phi \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{171}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<4.1 \times 10^{-4}$	90	0	[101] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[101] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.4 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_{172}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.1 \times 10^{-4}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.7 \times 10^{-3}$	90		ADLER	89C	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{173}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<2.6 \times 10^{-4}$	90	2	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6.7 \times 10^{-4}$	90	1	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\overline{K}^*(892)^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_{174}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.4 \times 10^{-4}$	90	1	[102] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[102] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.0 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^*(892)^0 \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{175}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.18 \times 10^{-3}$	90	1	[103] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[103] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 1.0 \times 10^{-3}$ using a photon pole amplitude model.

$\Gamma(\pi^+\pi^-\pi^0 \mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{176}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8.1 \times 10^{-4}$	90	1	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(\mu^\pm e^\mp)/\Gamma_{\text{total}}$ Γ_{177}/Γ

A test of lepton family number conservation.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$< 1.9 \times 10^{-5}$	90	2	[104] FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.0 \times 10^{-4}$	90	4	ALBRECHT	88G	ARG	e^+e^- 10 GeV
$< 2.7 \times 10^{-4}$	90	9	HAAS	88	CLEO	e^+e^- 10 GeV
$< 1.2 \times 10^{-4}$	90		BECKER	87C	MRK3	e^+e^- 3.77 GeV
$< 9 \times 10^{-4}$	90		PALKA	87	SILI	200 GeV πp
$<21 \times 10^{-4}$	90	0	[105] RILES	87	MRK2	e^+e^- 29 GeV

[104] This is the corrected result given in the erratum to FREYBERGER 96.

[105] RILES 87 assumes $B(D \to K\pi) = 3.0\%$ and has production model dependency.

$\Gamma(\pi^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{178}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8.6 \times 10^{-5}$	90	2	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{179}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.0 \times 10^{-4}$	90	0	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\rho^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{180}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<4.9 \times 10^{-5}$	90	0	[106] FREYBERGER 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[106] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 5.0 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\omega e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{181}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	0	[107] FREYBERGER 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[107] This FREYBERGER 96 limit is obtained using a phase-space model. The same limit is obtained using a photon pole amplitude model.

$\Gamma(\phi e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{182}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<3.4 \times 10^{-5}$	90	0	[108] FREYBERGER 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[108] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 3.3 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{183}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-4}$	90	0	FREYBERGER 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\overline{K}^*(892)^0 e^\pm \mu^\mp)/\Gamma_{\text{total}}$ Γ_{184}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-4}$	90	0	[109] FREYBERGER 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

[109] This FREYBERGER 96 limit is obtained using a phase-space model. The same limit is obtained using a photon pole amplitude model.

D^0 *CP*-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(K^+K^-)$ in $D^0, \overline{D}^0 \to K^+K^-$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths. The D^0 and $\overline{D}^0$ are distinguished by the charge of the parent D^*: $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.026±0.035 OUR AVERAGE					
−0.010±0.049±0.012	609	[110] AITALA	98C	E791	$-0.093 < A_{CP} < +0.073$ (90% CL)
+0.080±0.061		BARTELT	95	CLE2	$-0.022 < A_{CP} < +0.18$ (90%CL)
+0.024±0.084		[110] FRABETTI	94I	E687	$-0.11 < A_{CP} < +0.16$ (90% CL)

[110] AITALA 98C and FRABETTI 94I measure $N(D^0 \to K^+K^-)/N(D^0 \to K^-\pi^+)$, the ratio of numbers of events observed, and similarly for the $\overline{D}^0$.

$A_{CP}(\pi^+\pi^-)$ in $D^0, \overline{D}^0 \to \pi^+\pi^-$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths. The D^0 and $\overline{D}^0$ are distinguished by the charge of the parent D^*: $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.049±0.078±0.030	343	[111] AITALA	98C	E791	$-0.186 < A_{CP} < +0.088$ (90% CL)

[111] AITALA 98C measures $N(D^0 \to \pi^+\pi^-)/N(D^0 \to K^-\pi^+)$, the ratio of numbers of events observed, and similarly for the $\overline{D}^0$.

$A_{CP}(K^0_S\phi)$ in $D^0, \overline{D}^0 \to K^0_S\phi$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths. The D^0 and $\overline{D}^0$ are distinguished by the charge of the parent D^*: $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$.

VALUE	DOCUMENT ID		TECN	COMMENT
−0.028±0.094	BARTELT	95	CLE2	$-0.182 < A_{CP} < +0.126$ (90%CL)

$A_{CP}(K^0_S\pi^0)$ in $D^0, \overline{D}^0 \to K^0_S\pi^0$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths. The D^0 and $\overline{D}^0$ are distinguished by the charge of the parent D^*: $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$.

VALUE	DOCUMENT ID		TECN	COMMENT
−0.018±0.030	BARTELT	95	CLE2	$-0.067 < A_{CP} < +0.031$ (90%CL)

D^0 PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of D^0 mesons at or near the $\psi(3770)$ peak in e^+e^- production.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.8 ±0.5 ±0.6	[112] ADLER	88C	MRK3	e^+e^- 3.768 GeV
7.3 ±1.3	[113] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
8.00±0.95±1.21	[114] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
11.5 ±2.5	[115] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[112] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C find the ratio of cross sections (neutral to charged) to be 1.36 ± 0.23 ± 0.14.

[113] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[114] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[115] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

D^0 REFERENCES

AITALA	98	PR D57 13	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
AITALA	98C	PL B421 405	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
AITALA	98D	PL B423 185	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
ARTUSO	98	PRL 80 3193	M. Artuso+	(CLEO Collab.)
PDG	98	EPJ C3 1	C. Caso+	
ADAMOVICH	97	PL B408 469	+Alexandrov, Angelini+	(CERN BEATRICE Collab.)
BARATE	97C	PL B403 367	+Buskulic, Decamp, Ghez+	(ALEPH Collab.)
AITALA	96C	PRL 77 2384	+Amato, Anjos, Appel+	(FNAL E791 Collab.)
ALBRECHT	96C	PL B374 249	+Hamacher, Hofmann+	(ARGUS Collab.)
ALEXOPOU...	96	PRL 77 2380	Alexopoulos, Antoniazzi+	(FNAL E771 Collab.)
ASNER	96B	PR D54 4211	+Athanas, Bliss, Brower+	(CLEO Collab.)
BARISH	96	PL B373 334	+Chadha, Chan, Eigen+	(CLEO Collab.)
FRABETTI	96B	PL B382 312	+Cheung, Cumalat+	(FNAL E687 Collab.)
FREYBERGER	96	PRL 76 3065	+Gibaut, Kinoshita+	(CLEO Collab.)
Also	96B	PRL 77 2147 (errata)		
KUBOTA	96B	PR D54 2994	+Lattery, Nelson, Patton+	(CLEO Collab.)
ADAMOVICH	95	PL B353 563	+Adinolfi, Alexandrov+	(CERN BEATRICE Collab.)
BARTELT	95	PR D52 4860	+Csorna, Egyed, Jain+	(CLEO Collab.)
BUTLER	95	PR D52 2656	+Fu, Nemati, Ross, Skubic+	(CLEO Collab.)
FRABETTI	95C	PL B354 486	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95G	PL B364 127	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	94	PL B324 249	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	94F	PL B340 125	+Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	94I	ZPHY C64 375	+Hamacher, Hofmann+	(ARGUS Collab.)
CINABRO	94	PRL 72 1406	+Henderson, Liu, Saulnier+	(CLEO Collab.)
FRABETTI	94C	PL B321 295	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94D	PL B323 459	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94G	PL B331 217	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94I	PR D50 R2953	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94J	PL B340 254	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	94	PL B336 605	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
MISHRA	94	PR D50 R9	+Brown, Cooper+	(FNAL E789 Collab.)
AKERIB	93	PRL 71 3070	+Barish, Chadha, Chan+	(CLEO Collab.)
ALBRECHT	93D	PL B308 435	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ANJOS	93	PR D48 56	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
BEAN	93C	PL B317 647	+Gronberg, Kutschke, Menary+	(CLEO Collab.)
FRABETTI	93I	PL B315 203	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
KODAMA	93B	PL B313 260	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
PROCARIO	93B	PR D48 4007	+Yang, Akerib, Barish+	(CLEO Collab.)
SELEN	93	PRL 71 1973	+Sadoff, Ammar, Ball+	(CLEO Collab.)
ADAMOVICH	92	PL B280 163	+Alexandrov, Antinori+	(CERN WA82 Collab.)
ALBRECHT	92P	ZPHY C56 7	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
ANJOS	92B	PR D46 R1	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	92C	PR D46 1941	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
BARLAG	92C	ZPHY C55 383	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
Also	90D	ZPHY C48 29	Barlag, Becker, Boehringer, Bosman+	(ACCMOR Collab.)
COFFMAN	92B	PR D45 2196	+DeJongh, Dubois, Eigen+	(Mark III Collab.)
Also	90	PRL 64 2615	Adler, Blaylock, Bolton+	(Mark III Collab.)
FRABETTI	92	PL B281 167	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
FRABETTI	92B	PL B286 195	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
ALVAREZ	91B	ZPHY C50 11	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
AMMAR	91	PR D44 3383	+Baringer, Coppage, Davis+	(CLEO Collab.)
ANJOS	91	PR D43 R635	+Appel, Bean, Bracker+	(FNAL-TPS Collab.)
ANJOS	91D	PR D44 R3371	+Appel, Bean, Bracker+	(FNAL-TPS Collab.)
BAI	91	PRL 66 1011	+Bolton, Brown, Bunnell+	(Mark III Collab.)
COFFMAN	91	PL B263 135	+DeJongh, Dubois, Eigen, Hitlin+	(Mark III Collab.)
CRAWFORD	91B	PR D44 3394	+Fulton, Gan, Jensen+	(CLEO Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
FRABETTI	91	PL B263 584	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
KINOSHITA	91	PR D43 2836	+Pipkin, Procario, Wilson+	(CLEO Collab.)
KODAMA	91	PRL 66 1819	+Ushida, Mokhtarani, Paolone+	(FNAL E653 Collab.)
ALBRECHT	90C	ZPHY C46 9	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALEXANDER	90	PRL 65 1184	+Artuso, Bebek, Berkelman+	(CLEO Collab.)
ALEXANDER	90B	PRL 65 1531	+Artuso, Bebek, Berkelman+	(CLEO Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90D	PR D42 2414	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
BARLAG	90C	ZPHY C46 563	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ADLER	89	PRL 62 1821	+Becker, Blaylock, Bolton+	(Mark III Collab.)
ADLER	89C	PR D40 906	+Bai, Becker, Blaylock, Bolton+	(Mark III Collab.)
ALBRECHT	89D	ZPHY C43 181	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ANJOS	89F	PRL 62 1587	+Appel, Bean, Bracker, Browder+	(FNAL E691 Collab.)

ABACHI	88	PL B205 411	+Akerlof, Baringer+	(HRS Collab.)
ADLER	88	PR D37 2023	+Becker, Blaylock+	(Mark III Collab.)
ADLER	88C	PRL 60 89	+Becker, Blaylock+	(Mark III Collab.)
ALBRECHT	88G	PL B209 380	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
AMENDOLIA	88	EPL 5 407	+Bagliesi, Batignani+	(NA1 Collab.)
ANJOS	88C	PRL 60 1239	+Appel+	(FNAL E691 Collab.)
BORTOLETTO	88	PR D37 1719	+Goldberg, Horwitz, Mestayer, Moneti+	(CLEO Collab.)
Also	89D	PR D39 1471 erratum		
CUMALAT	88	PL B210 253	+Shipbaugh, Binkley+	(E-400 Collab.)
HAAS	88	PRL 60 1614	+Hempstead, Jensen+	(CLEO Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL E691 Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
ADLER	87	PL B196 107	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AGUILAR-...	87D	PL B193 140	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
AGUILAR-...	87E	ZPHY C36 551	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
AGUILAR-...	87F	ZPHY C36 559	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88	ZPHY C38 520 erratum		
ALBRECHT	87E	ZPHY C33 359	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87K	PL B199 447	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
BARLAG	87B	ZPHY C37 17	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
BECKER	87C	PL B193 147	+Blaylock, Bolton, Brown+	(Mark III Collab.)
Also	87D	PL B198 590 erratum	Becker, Blaylock, Bolton+	(Mark III Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
PALKA	87	PL B189 238	+Bailey, Becker, Belau+	(ACCMOR Collab.)
RILES	87	PR D35 2914	+Dorfan, Abrams, Amidei+	(Mark II Collab.)
ABACHI	86D	PL B182 101	+Akerlof, Baringer, Ballam+	(HRS Collab.)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
BAILEY	86	ZPHY C30 51	+Belau, Boehringer, Bosman+	(ACCMOR Collab.)
BEBEK	86	PRL 56 1893	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
GLADNEY	86	PR D34 2601	+Jaros, Ong, Barklow+	(Mark II Collab.)
LOUIS	86	PRL 56 1027	+Adolphsen, Alexander+	(PRIN, CHIC, ISU)
USHIDA	86B	PRL 56 1771	+Kondo+	(AICH, FNAL, KOBE, SEOU, MCGI+)
ALBRECHT	85B	PL 158B 525	+Binder, Harder, Philipp+	(ARGUS Collab.)
ALBRECHT	85F	PL 150B 235	+Binder, Harder, Philipp+	(ARGUS Collab.)
AUBERT	85	PL 155B 461	+Bassompierre, Becks, Benchouk+	(EMC Collab.)
BAILEY	85	ZPHY C28 357	+Belau, Boehringer, Bosman+	(ABCCMR Collab.)
BALTRUSAIT...	85B	PRL 54 1976	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BALTRUSAIT...	85E	PRL 55 150	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BENVENUTI	85	PL 158B 531	+Bollini, Bruni, Camporesi+	(BCDMS Collab.)
YAMAMOTO	85	PRL 54 522	+Yamamoto, Atwood, Baillon+	(DELCO Collab.)
ADAMOVICH	84B	PL 140B 123	+Alexandrov, Bravo+	(CERN WA58 Collab.)
ALTHOFF	84B	PL 138B 317	+Braunschweig, Kirschfink+	(TASSO Collab.)
DERRICK	84	PRL 53 1971	+Fernandez, Fries, Hyman+	(HRS Collab.)
PARTRIDGE	84	Thesis CALT-68-1150		(Crystal Ball Collab.)
SUMMERS	84	PRL 52 410	+	(UCSB, CARL, COLO, FNAL, TNTO, OKLA, CNRC)
BAILEY	83B	PL 132B 237	+Bardsley, Becker, Blanar+	(ACCMOR Collab.)
BODEK	82	PL 113B 82	+Breedon+	(ROCH, CIT, CHIC, FNAL, STAN)
FIORINO	81	LNC 30 166	+	(Photon-Emulsion and Omega-Photon Collab.)
SCHINDLER	81	PR D24 78	+Alam, Boyarski, Breidenbach+	(Mark II Collab.)
TRILLING	81	PRPL 75 57		(LBL, UCB) J
ASTON	80E	PL 94B 113	+	(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
AVERY	80	PRL 44 1309	+Wiss, Butler, Gladding+	(ILL, FNAL, COLU)
SCHINDLER	80	PR D21 2716	+Siegrist, Alam, Boyarski+	(Mark II Collab.)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)
ABRAMS	79D	PRL 43 481	+Alam, Blocker, Boyarski+	(Mark II Collab.)
ATIYA	79	PRL 43 414	+Holmes, Knapp, Lee+	(COLU, ILL, FNAL)
BALTAY	78C	PRL 41 73	+Caroumbalis, French, Hibbs, Hylton+	(COLU, BNL)
VUILLEMIN	78	PRL 41 1149	+Feldman, Feller+	(Mark I Collab.)
FELDMAN	77B	PRL 38 1313	+Peruzzi, Piccolo, Abrams, Alam+	(Mark I Collab.)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(Mark I Collab.)
PICCOLO	77	PL 70B 260	+Peruzzi, Luth, Nguyen, Wiss, Abrams+	(Mark I Collab.)
RAPIDIS	77	PRL 39 526	+Gobbi, Luke, Barbaro-Galtieri+	(Mark I Collab.)
GOLDHABER	76	PRL 37 255	+Pierre, Abrams, Alam+	(Mark I Collab.)

OTHER RELATED PAPERS

RICHMAN	95	RMP 67 893	+Burchat	(UCSB, STAN)
ROSNER	95	CNPP 21 369		(CHIC)

$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

J consistent with 1, value 0 ruled out (NGUYEN 77).

$D^*(2007)^0$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2006.7±0.5 OUR FIT Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2006 ±1.5	[1] GOLDHABER 77	MRK1	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0.

$m_{D^*(2007)^0} - m_{D^0}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
142.12±0.07 OUR FIT				
142.12±0.07 OUR AVERAGE				
142.2 ±0.3 ±0.2	145	ALBRECHT 95F	ARG	$e^+e^- \rightarrow$ hadrons
142.12±0.05±0.05	1176	BORTOLETTO 92B	CLE2	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
142.2 ±2.0		SADROZINSKI 80	CBAL	$D^{*0} \rightarrow D^0\pi^0$
142.7 ±1.7		[2] GOLDHABER 77	MRK1	e^+e^-

[2] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0.

$D^*(2007)^0$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<2.1	90	[3] ABACHI 88B	HRS	$D^{*0} \rightarrow D^+\pi^-$

[3] Assuming $m_{D^{*0}}$ = 2007.2 ± 2.1 MeV/c^2.

$D^*(2007)^0$ DECAY MODES

$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^0$	(61.9±2.9) %
Γ_2	$D^0\gamma$	(38.1±2.9) %

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 3 measurements and one constraint to determine 2 parameters. The overall fit has a χ^2 = 0.5 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|c} x_2 & -100 \\ \hline & x_1 \end{array}$$

$D^*(2007)^0$ BRANCHING RATIOS

$\Gamma(D^0\pi^0)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.619±0.029 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.596±0.035±0.028	858	ALBRECHT 95F	ARG	$e^+e^- \rightarrow$ hadrons
0.636±0.023±0.033	1097	[4] BUTLER 92	CLE2	$e^+e^- \rightarrow$ hadrons

$\Gamma(D^0\gamma)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.381±0.029 OUR FIT				
0.381±0.029 OUR AVERAGE				
0.404±0.035±0.028	456	ALBRECHT 95F	ARG	$e^+e^- \rightarrow$ hadrons
0.364±0.023±0.033	621	[4] BUTLER 92	CLE2	$e^+e^- \rightarrow$ hadrons
0.37 ±0.08 ±0.08		ADLER 88D	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.23		LOW 87	HRS	29 GeV e^+e^-
0.53 ±0.13		BARTEL 85G	JADE	e^+e^-, hadrons
0.47 ±0.12		COLES 82	MRK2	e^+e^-
0.45 ±0.15		GOLDHABER 77	MRK1	e^+e^-

[4] The BUTLER 92 branching ratios are not independent, they have been constrained by the authors to sum to 100%.

$D^*(2007)^0$ REFERENCES

ALBRECHT	95F	ZPHY C66 63	+Ehrlichmann+	(ARGUS Collab.)
BORTOLETTO	92B	PRL 69 2046	+Brown, Dominick+	(CLEO Collab.)
BUTLER	92	PRL 69 2041	+Fu, Kalbfleish+	(CLEO Collab.)
ABACHI	88B	PL B212 533	+Akerlof+	(ANL, IND, MICH, PURD, LBL)
ADLER	88D	PL B208 152	+Becker+	(Mark III Collab.)
LOW	87	PL B183 232	+Abachi, Akerlof, Baringer+	(HRS Collab.)
BARTEL	85G	PL 161B 197	+Dietrich, Ambrus+	(JADE Collab.)
COLES	82	PR D26 2190	+Abrams, Blocker, Blondel+	(LBL, SLAC)
SADROZINSKI	80	Madison Conf. 681	+	(PRIN, CIT, HARV, SLAC, STAN)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
NGUYEN	77	PRL 39 262	+Wiss, Abrams, Alam, Boyarski+	(LBL, SLAC) J

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
TRILLING	81	PRPL 75 57		(LBL, UCB)
GOLDHABER	76	PRL 37 255	+Pierre, Abrams, Alam+	(Mark I Collab.)

$D^*(2010)^\pm$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

$D^*(2010)^\pm$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2010.0±0.5 OUR FIT Error includes scale factor of 1.1.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2008 ±3	[1] GOLDHABER	77	MRK1	±	e^+e^-
2008.6±1.0	[2] PERUZZI	77	MRK1	±	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0; not independent of FELDMAN 77B mass difference below.

[2] PERUZZI 77 mass not independent of FELDMAN 77B mass difference below and PERUZZI 77 D^0 mass value.

$m_{D^*(2010)^+} - m_{D^+}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
140.64±0.10 OUR FIT	Error includes scale factor of 1.1.				
140.64±0.08±0.06	620	BORTOLETTO	92B	CLE2	$e^+e^- \rightarrow$ hadrons

$m_{D^*(2010)^+} - m_{D^0}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
145.397±0.030 OUR FIT					
145.397±0.030 OUR AVERAGE					
145.5 ±0.15	103	[3] ADLOFF	97B	H1	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.44 ±0.08	152	[3] BREITWEG	97	ZEUS	$D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^- 3\pi$
145.42 ±0.11	199	[3] BREITWEG	97	ZEUS	$D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^-\pi^+$
145.4 ±0.2	48	[3] DERRICK	95	ZEUS	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.39 ±0.06 ±0.03		BARLAG	92B	ACCM	π^- 230 GeV
145.5 ±0.2	115	[3] ALEXANDER	91B	OPAL	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.30 ±0.06		[3] DECAMP	91J	ALEP	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.40 ±0.05 ±0.10		ABACHI	88B	HRS	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.46 ±0.07 ±0.03		ALBRECHT	85F	ARG	$D^{*\pm} \rightarrow D^0\pi^+$
145.5 ±0.3	28	BAILEY	83	SPEC	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.5 ±0.3	60	FITCH	81	SPEC	π^- A
145.3 ±0.5	30	FELDMAN	77B	MRK1	$D^{*+} \rightarrow D^0\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
145.44 ±0.09	122	[3] BREITWEG	97B	ZEUS	$D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^-\pi^+$
145.8 ±1.5	16	AHLEN	83	HRS	$D^{*+} \rightarrow D^0\pi^+$
145.1 ±1.8	12	BAILEY	83	SPEC	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.1 ±0.5	14	BAILEY	83	SPEC	$D^{*\pm} \rightarrow D^0\pi^\pm$
145.5 ±0.5	14	YELTON	82	MRK2	29 $e^+e^- \rightarrow K^-\pi^+$
~ 145.5		AVERY	80	SPEC	γA
145.2 ±0.6	2	BLIETSCHAU	79	BEBC	νp

[3] Systematic error not evaluated.

$m_{D^*(2010)^+} - m_{D^*(2007)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6±1.8	[4] PERUZZI	77	MRK1	e^+e^-

[4] Not independent of FELDMAN 77B mass difference above, PERUZZI 77 D^0 mass, and GOLDHABER 77 $D^*(2007)^0$ mass.

$D^*(2010)^\pm$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.131	90	110	BARLAG	92B	ACCM	π^- 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.1	90		ABACHI	88B	HRS	$D^{*\pm} \rightarrow D^0\pi^\pm$
<2.2			YELTON	82	MRK2	$e^+e^- \rightarrow K^-\pi^+\pi^-$
<2.0	90	30	FELDMAN	77B	MRK1	$D^{*+} \rightarrow D^0\pi^+$

$D^*(2010)^\pm$ DECAY MODES

$D^*(2010)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	(68.3±1.4) %
Γ_2	$D^+\pi^0$	(30.6±2.5) %
Γ_3	$D^+\gamma$	$(1.1^{+2.1}_{-0.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 3 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 0.0 for 1 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_2 & -55 & \\ x_3 & 0 & -83 \\ \hline & x_1 & x_2 \end{array}$$

$D^*(2010)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.683±0.014 OUR FIT				
0.683±0.014 OUR AVERAGE				
0.688±0.024±0.013	ALBRECHT	95F	ARG	$e^+e^- \rightarrow$ hadrons
0.681±0.010±0.013	[5] BUTLER	92	CLE2	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.57 ±0.04 ±0.04	ADLER	88D	MRK3	e^+e^-
0.44 ±0.10	COLES	82	MRK2	e^+e^-
0.6 ±0.15	[6] GOLDHABER	77	MRK1	e^+e^-

$\Gamma(D^+\pi^0)/\Gamma_{\rm total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.306±0.025 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.312±0.011±0.008	1404	ALBRECHT	95F	ARG	$e^+e^- \rightarrow$ hadrons
0.308±0.004±0.008	410	[5] BUTLER	92	CLE2	$e^+e^- \rightarrow$ hadrons
0.26 ±0.02 ±0.02		ADLER	88D	MRK3	e^+e^-
0.34 ±0.07		COLES	82	MRK2	e^+e^-

$\Gamma(D^+\gamma)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.011^{+0.021}_{-0.007}$ OUR FIT						
0.011±0.014±0.016		12	[5] BUTLER	92	CLE2	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.052	90		ALBRECHT	95F	ARG	$e^+e^- \rightarrow$ hadrons
0.17 ±0.05 ±0.05			ADLER	88D	MRK3	e^+e^-
0.22 ±0.12			[7] COLES	82	MRK2	e^+e^-

[5] The BUTLER 92 branching ratios are not independent, they have been constrained by the authors to sum to 100%.

[6] Assuming that isospin is conserved in the decay.

[7] Not independent of $\Gamma(D^0\pi^+)/\Gamma_{\rm total}$ and $\Gamma(D^+\pi^0)/\Gamma_{\rm total}$ measurement.

$D^*(2010)^\pm$ REFERENCES

ADLOFF	97B	ZPHY C72 593	+Ald, Anderson+	(H1 Collab.)
BREITWEG	97	PL B401 192	+Derrick, Krakauer+	(ZEUS Collab.)
BREITWEG	97B	PL B407 402	J. Breitweg+	(ZEUS Collab.)
ALBRECHT	95F	ZPHY C66 63	+Ehrlichmann+	(ARGUS Collab.)
DERRICK	95	PL B349 225	+Krakauer+	(ZEUS Collab.)
BARLAG	92B	PL B278 480	+Becker, Bozek+	(ACCMOR Collab.)
BORTOLETTO	92B	PRL 69 2046	+Brown, Dominick+	(CLEO Collab.)
BUTLER	92	PRL 69 2041	+Fu, Kalbfleish+	(CLEO Collab.)
ALEXANDER	91B	PL B262 341	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ABACHI	88B	PL B212 533	+Akerlof+	(ANL, IND, MICH, PURD, LBL)
ADLER	88D	PL B208 152	+Becker+	(Mark III Collab.)
ALBRECHT	85F	PL 150B 235	+Binder, Harder, Philipp+	(ARGUS Collab.)
AHLEN	83	PRL 51 1147	+Akerlof+	(ANL, IND, LBL, MICH, PURD, SLAC)
BAILEY	83	PL 132B 230	+Bardsley+	(AMST, BRIS, CERN, CRAC, MPIM+)
COLES	82	PR D26 2190	+Abrams, Blocker, Blondel+	(LBL, SLAC)
YELTON	82	PRL 49 430	+Feldman, Goldhaber+	(SLAC, LBL, UCB, HARV)
FITCH	81	PRL 46 761	+Devaux, Cavaglia, May+	(PRIN, SACL, TORI, BNL)
AVERY	80	PRL 44 1309	+Wiss, Butler, Gladding+	(ILL, FNAL, COLU)
BLIETSCHAU	79	PL 86B 108	+	(AACH3, BONN, CERN, MPIM, OXF)
FELDMAN	77B	PRL 38 1313	+Peruzzi, Piccolo, Abrams, Alam+	(Mark I Collab.)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(Mark I Collab.)

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
BEBEK	82	PRL 49 610	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
TRILLING	81	PRPL 75 57		(LBL, UCB)
PERUZZI	76	PRL 37 569	+Piccolo, Feldman, Nguyen, Wiss+	(Mark I Collab.)

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+\pi^-$. $J^P = 1^+$ according to ALBRECHT 89H.

$D_1(2420)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2422.2±1.8 OUR AVERAGE	Error includes scale factor of 1.2.				
$2421\ ^{+1}_{-2}\ \pm 2$	286	AVERY	94C	CLE2	$e^+e^- \to D^{*+}\pi^- X$
$2422\ \pm 2\ \pm 2$	51	FRABETTI	94B	E687	$\gamma \mathrm{Be} \to D^{*+}\pi^- X$
$2428\ \pm 3\ \pm 2$	279	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
$2414\ \pm 2\ \pm 5$	171	ALBRECHT	89H	ARG	$e^+e^- \to D^{*+}\pi^- X$
$2428\ \pm 8\ \pm 5$	171	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^- X$

$D_1(2420)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$18.9\ ^{+4.6}_{-3.5}$ OUR AVERAGE					
$20\ ^{+6}_{-5}\ \pm 3$	286	AVERY	94C	CLE2	$e^+e^- \to D^{*+}\pi^- X$
$15\ \pm 8\ \pm 4$	51	FRABETTI	94B	E687	$\gamma \mathrm{Be} \to D^{*+}\pi^- X$
$23\ ^{+8}_{-6}\ ^{+10}_{-3}$	279	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
$13\ \pm 6\ ^{+10}_{-5}$	171	ALBRECHT	89H	ARG	$e^+e^- \to D^{*+}\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$58\ \pm 14\ \pm 10$	171	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^- X$

$D_1(2420)^0$ DECAY MODES

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+\pi^-$	seen
Γ_2	$D^+\pi^-$	not seen

$D_1(2420)^0$ BRANCHING RATIOS

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{\mathrm{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \to D^*\pi^- X$
seen	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ **Γ_2/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.24	90	AVERY	90	CLEO	$e^+e^- \to D^+\pi^- X$

$D_1(2420)^0$ REFERENCES

AVERY	94C	PL B331 236	+Freyberger, Rodriguez+	(CLEO Collab.)
FRABETTI	94B	PRL 72 324	+Cheung, Cumalat+	(FNAL E687 Collab.)
AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89H	PL B232 398	+Glaser, Harder+	(ARGUS Collab.) JP
ANJOS	89C	PRL 62 1717	+Appel+	(FNAL E691 Collab.)

$D_1(2420)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Seen in $D^*(2007)^0\pi^+$. $J^P = 0^+$ ruled out.

$D_1(2420)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2427±5 OUR AVERAGE	Error includes scale factor of 2.0.				
$2425 \pm 2 \pm 2$	146	BERGFELD	94B	CLE2	$e^+e^- \to D^{*0}\pi^+ X$
$2443 \pm 7 \pm 5$	190	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+ X^0$

$m_{D_1^*(2420)^\pm} - m_{D_1^*(2420)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$4\ ^{+2}_{-3} \pm 3$	BERGFELD	94B	CLE2	$e^+e^- \to$ hadrons

$D_1(2420)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
28± 8 OUR AVERAGE					
$26\ ^{+8}_{-7} \pm 4$	146	BERGFELD	94B	CLE2	$e^+e^- \to D^{*0}\pi^+ X$
$41 \pm 19 \pm 8$	190	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+ X^0$

$D_1(2420)^\pm$ DECAY MODES

$D_1^*(2420)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2007)^0\pi^+$	seen
Γ_2	$D^0\pi^+$	not seen

$D_1(2420)^\pm$ BRANCHING RATIOS

$\Gamma(D^*(2007)^0\pi^+)/\Gamma_{\mathrm{total}}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+ X^0$

$\Gamma(D^0\pi^+)/\Gamma(D^*(2007)^0\pi^+)$ **Γ_2/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.18	90	BERGFELD	94B	CLE2	$e^+e^- \to$ hadrons

$D_1(2420)^\pm$ REFERENCES

BERGFELD	94B	PL B340 194	+Eisenstein, Gollin+	(CLEO Collab.)
ANJOS	89C	PRL 62 1717	+Appel+	(FNAL E691 Collab.)

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

$D_2^*(2460)0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2458.9±2.0 OUR AVERAGE	Error includes scale factor of 1.2.			
2465 ±3 ±3	486	AVERY 94C	CLE2	$e^+e^- \rightarrow D^+\pi^-X$
2453 ±3 ±2	128	FRABETTI 94B	E687	$\gamma Be \rightarrow D^+\pi^-X$
2461 ±3 ±1	440	AVERY 90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^-X$
2455 ±3 ±5	337	ALBRECHT 89B	ARG	$e^+e^- \rightarrow D^+\pi^-X$
2459 ±3 ±2	153	ANJOS 89C	TPS	$\gamma N \rightarrow D^+\pi^-X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2466 ±7	1	ASRATYAN 95	BEBC	53,40 $\nu(\overline{\nu}) \rightarrow p + X$, $d + X$

$D_2^*(2460)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
23± 5 OUR AVERAGE				
$28^{+\ 8}_{-\ 7}\pm\ 6$	486	AVERY 94C	CLE2	$e^+e^- \rightarrow D^+\pi^-X$
25±10± 5	128	FRABETTI 94B	E687	$\gamma Be \rightarrow D^+\pi^-X$
$20^{+\ 9}_{-12}{}^{+\ 9}_{-10}$	440	AVERY 90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^-X$
$15^{+13}_{-10}{}^{+\ 5}_{-10}$	337	ALBRECHT 89B	ARG	$e^+e^- \rightarrow D^+\pi^-X$
20±10± 5	153	ANJOS 89C	TPS	$\gamma N \rightarrow D^+\pi^-X$

$D_2^*(2460)^0$ DECAY MODES

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^+\pi^-$	seen
Γ_2	$D^*(2010)^+\pi^-$	seen

$D_2^*(2460)^0$ BRANCHING RATIOS

$\Gamma(D^+\pi^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	337	ALBRECHT 89B	ARG	$e^+e^- \rightarrow D^+\pi^-X$
seen		ANJOS 89C	TPS	$\gamma N \rightarrow D^+\pi^-X$

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	AVERY 90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^-X$
seen	ALBRECHT 89H	ARG	$e^+e^- \rightarrow D^*\pi^-X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
2.3±0.6 OUR AVERAGE			
2.2±0.7±0.6	AVERY 94C	CLE2	$e^+e^- \rightarrow D^{*+}\pi^-X$
2.3±0.8	AVERY 90	CLEO	e^+e^-
3.0±1.1±1.5	ALBRECHT 89H	ARG	$e^+e^- \rightarrow D^*\pi^-X$

$D_2^*(2460)^0$ REFERENCES

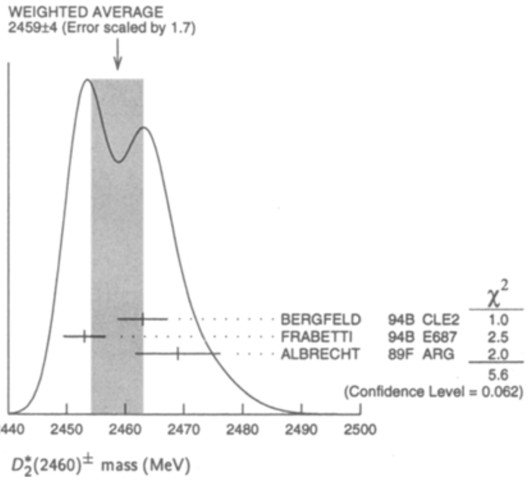
ASRATYAN 95 ZPHY C68 43 + (BIRM, BELG, CERN, SERP, ITEP, MPIM, RAL)
AVERY 94C PL B331 236 +Freyberger, Rodriguez+ (CLEO Collab.)
FRABETTI 94B PRL 72 324 +Cheung, Cumalat+ (FNAL E687 Collab.)
AVERY 90 PR D41 774 +Besson (CLEO Collab.)
ALBRECHT 89B PL B221 422 +Boeckmann+ (ARGUS Collab.) JP
ALBRECHT 89H PL B232 398 +Glaser, Harder+ (ARGUS Collab.) JP
ANJOS 89C PRL 62 1717 +Appel+ (FNAL E691 Collab.)

$D_2^*(2460)^{\pm}$

$I(J^P) = \frac{1}{2}(2^+)$

$D_2^*(2460)^{\pm}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2459±4 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.			
2463±3±3	310	BERGFELD 94B	CLE2	$e^+e^- \rightarrow D^0\pi^+X$
2453±3±2	185	FRABETTI 94B	E687	$\gamma Be \rightarrow D^0\pi^+X$
2469±4±6		ALBRECHT 89F	ARG	$e^+e^- \rightarrow D^0\pi^+X$



$m_{D_2^*(2460)^{\pm}} - m_{D_2^*(2460)^0}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.9±3.3 OUR AVERAGE	Error includes scale factor of 1.1.		
− 2 ±4 ±4	BERGFELD 94B	CLE2	$e^+e^- \rightarrow$ hadrons
0 ±4	FRABETTI 94B	E687	$\gamma Be \rightarrow D\pi X$
14 ±5 ±8	ALBRECHT 89F	ARG	$e^+e^- \rightarrow D^0\pi^+X$

$D_2^*(2460)^{\pm}$WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$25^{+\ 8}_{-\ 7}$ OUR AVERAGE				
$27^{+11}_{-\ 8}\pm5$	310	BERGFELD 94B	CLE2	$e^+e^- \rightarrow D^0\pi^+X$
23± 9±5	185	FRABETTI 94B	E687	$\gamma Be \rightarrow D^0\pi^+X$

$D_2^*(2460)^{\pm}$ DECAY MODES

$D_2^*(2460)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	seen
Γ_2	$D^{*0}\pi^+$	seen

$D_2^*(2460)^{\pm}$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	ALBRECHT 89F	ARG	$e^+e^- \rightarrow D^0\pi^+X$

$\Gamma(D^0\pi^+)/\Gamma(D^{*0}\pi^+)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
1.9±1.1±0.3	BERGFELD 94B	CLE2	$e^+e^- \rightarrow$ hadrons

$D_2^*(2460)^{\pm}$ REFERENCES

BERGFELD 94B PL B340 194 +Eisenstein, Gollin+ (CLEO Collab.)
FRABETTI 94B PRL 72 324 +Cheung, Cumalat+ (FNAL E687 Collab.)
ALBRECHT 89F PL B231 208 +Glaeser+ (ARGUS Collab.)

CHARMED, STRANGE MESONS
($C = S = \pm1$)

$D_s^+ = c\bar{s}$, $D_s^- = \bar{c}s$, similarly for D_s^*'s

$D_s^{\pm}$
was $F^{\pm}$

$I(J^P) = 0(0^-)$

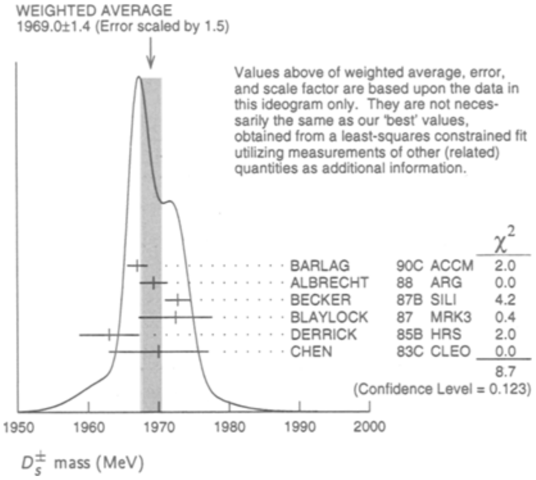
The angular distributions of the decays of the ϕ and $\overline{K}^*(892)^0$ in the $\phi\pi^+$ and $K^+\overline{K}^*(892)^0$ modes strongly indicate that the spin is zero. The parity given is that expected of a $c\bar{s}$ ground state.

$D_s^{\pm}$ MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements. Measurements of the $D_s^{\pm}$ mass with an error greater than 10 MeV are omitted from the fit and average. A number of early measurements have been omitted altogether.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1968.5± 0.6 OUR FIT Error includes scale factor of 1.1.				
1969.0± 1.4 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
1967.0± 1.0± 1.0	54	BARLAG 90C	ACCM	π^- Cu 230 GeV
1969.3± 1.4± 1.4		ALBRECHT 88	ARG	e^+e^- 9.4–10.6 GeV
1972.7± 1.5± 1.0	21	BECKER 87B	SILI	200 GeV π,K,p
1972.4± 3.7± 3.7	27	BLAYLOCK 87	MRK3	e^+e^- 4.14 GeV
1963 ± 3 ± 3	30	DERRICK 85B	HRS	e^+e^- 29 GeV
1970 ± 5 ± 5	104	CHEN 83C	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1968.3± 0.7± 0.7	290	[1] ANJOS 88	E691	Photoproduction
1980 ±15	6	USHIDA 86	EMUL	ν wideband
1973.6± 2.6± 3.0	163	ALBRECHT 85D	ARG	e^+e^- 10 GeV
1948 ±28 ±10	65	AIHARA 84D	TPC	e^+e^- 29 GeV
1975 ± 9 ±10	49	ALTHOFF 84	TASS	e^+e^- 14–25 GeV
1975 ± 4	3	BAILEY 84	ACCM	hadron$^+$ Be → $\phi\pi^+$X

[1] ANJOS 88 enters the fit via $m_{D_s^{\pm}} - m_{D^{\pm}}$ (see below).



$m_{D_s^{\pm}} - m_{D^{\pm}}$

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
99.2±0.5 OUR FIT Error includes scale factor of 1.1.				
99.2±0.5 OUR AVERAGE				
99.5±0.6±0.3		BROWN 94	CLE2	$e^+e^- \approx \Upsilon(4S)$
98.5±1.5	555	CHEN 89	CLEO	e^+e^- 10.5 GeV
99.0±0.8	290	ANJOS 88	E691	Photoproduction

$D_s^{\pm}$ MEAN LIFE

Measurements with an error greater than 0.2×10^{-12} s are omitted from the average.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.467±0.017 OUR AVERAGE				
0.475±0.020±0.007	900	FRABETTI 93F	E687	γBe, $D_s^+ \rightarrow \phi\pi^+$
$0.33\ ^{+0.12}_{-0.08}\ \pm0.03$	15	ALVAREZ 90	NA14	γ, $D_s^+ \rightarrow \phi\pi^+$
$0.469\ ^{+0.102}_{-0.086}$	54	[2] BARLAG 90C	ACCM	π^- Cu 230 GeV
0.50 ±0.06 ±0.03	104	FRABETTI 90	E687	γBe, $\phi\pi^+$
$0.56\ ^{+0.13}_{-0.12}\ \pm0.08$	144	ALBRECHT 88I	ARG	e^+e^- 10 GeV
0.47 ±0.04 ±0.02	228	RAAB 88	E691	Photoproduction
$0.33\ ^{+0.10}_{-0.06}$	21	[3] BECKER 87B	SILI	200 GeV π,K,p
$0.26\ ^{+0.16}_{-0.09}$	6	USHIDA 86	EMUL	ν wideband
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.31\ ^{+0.24}_{-0.20}\ \pm0.05$	18	AVERILL 89	HRS	e^+e^- 29 GeV
$0.48\ ^{+0.06}_{-0.05}\ \pm0.02$	99	ANJOS 87B	E691	See RAAB 88
$0.57\ ^{+0.36}_{-0.26}\ \pm0.09$	9	BRAUNSCH... 87	TASS	e^+e^- 35–44 GeV
0.47 ±0.22 ±0.05	141	CSORNA 87	CLEO	e^+e^- 10 GeV
$0.35\ ^{+0.24}_{-0.18}\ \pm0.09$	17	JUNG 86	HRS	See AVERILL 89
$0.32\ ^{+0.30}_{-0.13}$	3	BAILEY 84	ACCM	hadron$^+$ Be → $\phi\pi^+$X
$0.19\ ^{+0.13}_{-0.07}$	4	USHIDA 83	EMUL	See USHIDA 86

[2] BARLAG 90C estimates the systematic error to be negligible.
[3] BECKER 87B estimates the systematic error to be negligible.

D_s^+ DECAY MODES

Branching fractions for modes with a resonance in the final state include all the decay modes of the resonance. D_s^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes			
Γ_1	K^- anything		$(13\ ^{+14}_{-12})$ %	
Γ_2	$\overline{K}^0$ anything + K^0 anything		(39 ± 28) %	
Γ_3	K^+ anything		$(20\ ^{+18}_{-14})$ %	
Γ_4	non-$K\overline{K}$ anything		(64 ± 17) %	
Γ_5	e^+ anything		$(8\ ^{+6}_{-5})$ %	
Γ_6	ϕ anything		$(18\ ^{+15}_{-10})$ %	
	Leptonic and semileptonic modes			
Γ_7	$\mu^+\nu_\mu$		$(4.0\ ^{+2.2}_{-2.0}) \times 10^{-3}$	S=1.4
Γ_8	$\tau^+\nu_\tau$		(7 ± 4) %	
Γ_9	$\phi\ell^+\nu_\ell$	[a]	(2.0 ± 0.5) %	
Γ_{10}	$\eta\ell^+\nu_\ell + \eta'(958)\ell^+\nu_\ell$	[a]	(3.4 ± 1.0) %	
Γ_{11}	$\eta\ell^+\nu_\ell$		(2.5 ± 0.7) %	
Γ_{12}	$\eta'(958)\ell^+\nu_\ell$		$(8.8 \pm 3.4) \times 10^{-3}$	
	Hadronic modes with a $K\overline{K}$ pair (including from a ϕ)			
Γ_{13}	$K^+\overline{K}^0$		(3.6 ± 1.1) %	
Γ_{14}	$K^+K^-\pi^+$	[b]	(4.4 ± 1.2) %	S=1.1
Γ_{15}	$\phi\pi^+$	[c]	(3.6 ± 0.9) %	
Γ_{16}	$K^+\overline{K}^*(892)^0$	[c]	(3.3 ± 0.9) %	
Γ_{17}	$f_0(980)\pi^+$	[c]	(1.8 ± 0.8) %	S=1.3
Γ_{18}	$K^+\overline{K}_0^*(1430)^0$	[c]	$(7 \pm 4) \times 10^{-3}$	
Γ_{19}	$f_J(1710)\pi^+ \rightarrow K^+K^-\pi^+$	[d]	$(1.5 \pm 1.9) \times 10^{-3}$	
Γ_{20}	$K^+K^-\pi^+$ nonresonant		$(9 \pm 4) \times 10^{-3}$	
Γ_{21}	$K^0\overline{K}^0\pi^+$		—	
Γ_{22}	$K^*(892)^+\overline{K}^0$	[c]	(4.3 ± 1.4) %	
Γ_{23}	$K^+K^-\pi^+\pi^0$		—	
Γ_{24}	$\phi\pi^+\pi^0$	[c]	(9 ± 5) %	

Γ_{25}	$\phi\rho^+$		[c]	(6.7 ± 2.3) %	
Γ_{26}	$\phi\pi^+\pi^0$ 3-body		[c]	< 2.6 %	CL=90%
Γ_{27}	$K^+K^-\pi^+\pi^0$ non-ϕ			< 9 %	CL=90%
Γ_{28}	$K^+\overline{K}^0\pi^+\pi^-$			< 2.8 %	CL=90%
Γ_{29}	$K^0K^-\pi^+\pi^+$			(4.3 ± 1.5) %	
Γ_{30}	$K^*(892)^+\overline{K}^*(892)^0$		[c]	(5.8 ± 2.5) %	
Γ_{31}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$			< 2.9 %	CL=90%
Γ_{32}	$K^+K^-\pi^+\pi^+\pi^-$			$(8.3 \pm 3.3) \times 10^{-3}$	
Γ_{33}	$\phi\pi^+\pi^+\pi^-$		[c]	(1.18 ± 0.35) %	
Γ_{34}	$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ			$(3.0 {}^{+3.0}_{-2.0}) \times 10^{-3}$	

Hadronic modes without K's

Γ_{35}	$\pi^+\pi^+\pi^-$			(1.0 ± 0.4) %	S=1.2
Γ_{36}	$\rho^0\pi^+$			$< 8 \times 10^{-4}$	CL=90%
Γ_{37}	$f_0(980)\pi^+$		[c]	(1.8 ± 0.8) %	S=1.7
Γ_{38}	$f_2(1270)\pi^+$		[c]	$(2.3 \pm 1.3) \times 10^{-3}$	
Γ_{39}	$f_0(1500)\pi^+ \rightarrow \pi^+\pi^-\pi^+$		[e]	$(2.8 \pm 1.6) \times 10^{-3}$	
Γ_{40}	$\pi^+\pi^+\pi^-$ nonresonant			$< 2.8 \times 10^{-3}$	CL=90%
Γ_{41}	$\pi^+\pi^+\pi^-\pi^0$			< 12 %	CL=90%
Γ_{42}	$\eta\pi^+$		[c]	(2.0 ± 0.6) %	
Γ_{43}	$\omega\pi^+$		[c]	$(3.1 \pm 1.4) \times 10^{-3}$	
Γ_{44}	$\pi^+\pi^+\pi^+\pi^-\pi^-$			$(6.9 \pm 3.0) \times 10^{-3}$	
Γ_{45}	$\pi^+\pi^+\pi^-\pi^0\pi^0$			—	
Γ_{46}	$\eta\rho^+$		[c]	(10.3 ± 3.2) %	
Γ_{47}	$\eta\pi^+\pi^0$ 3-body		[c]	< 3.0 %	CL=90%
Γ_{48}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$			(4.9 ± 3.2) %	
Γ_{49}	$\eta'(958)\pi^+$		[c]	(4.9 ± 1.8) %	
Γ_{50}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$			—	
Γ_{51}	$\eta'(958)\rho^+$		[c]	(12 ± 4) %	
Γ_{52}	$\eta'(958)\pi^+\pi^0$ 3-body		[c]	< 3.1 %	CL=90%

Modes with one or three K's

Γ_{53}	$K^0\pi^+$			$< 8 \times 10^{-3}$	CL=90%
Γ_{54}	$K^+\pi^+\pi^-$			(1.0 ± 0.4) %	
Γ_{55}	$K^+\rho^0$			$< 2.9 \times 10^{-3}$	CL=90%
Γ_{56}	$K^*(892)^0\pi^+$		[c]	$(6.5 \pm 2.8) \times 10^{-3}$	
Γ_{57}	$K^+K^+K^-$			$< 6 \times 10^{-4}$	CL=90%
Γ_{58}	ϕK^+		[c]	$< 5 \times 10^{-4}$	CL=90%

$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes

Γ_{59}	$\pi^+\mu^+\mu^-$		[f]	$< 4.3 \times 10^{-4}$	CL=90%
Γ_{60}	$K^+\mu^+\mu^-$	$C1$		$< 5.9 \times 10^{-4}$	CL=90%
Γ_{61}	$K^*(892)^+\mu^+\mu^-$	$C1$		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{62}	$\pi^-\mu^+\mu^+$	L		$< 4.3 \times 10^{-4}$	CL=90%
Γ_{63}	$K^-\mu^+\mu^+$	L		$< 5.9 \times 10^{-4}$	CL=90%
Γ_{64}	$K^*(892)^-\mu^+\mu^+$	L		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{65}	A dummy mode used by the fit.			(80 ± 5) %	

[a] For now, we average together measurements of the $X e^+ \nu_e$ and $X \mu^+ \nu_\mu$ branching fractions. This is the *average*, not the *sum*.

[b] The branching fraction for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[c] This branching fraction includes all the decay modes of the final-state resonance.

[d] This value includes only K^+K^- decays of the $f_J(1710)$, because branching fractions of this resonance are not known.

[e] This value includes only $\pi^+\pi^-$ decays of the $f_0(1500)$, because branching fractions of this resonance are not known.

[f] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

CONSTRAINED FIT INFORMATION

An overall fit to 15 branching ratios uses 24 measurements and one constraint to determine 10 parameters. The overall fit has a $\chi^2 = 17.8$ for 15 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_9	45								
x_{11}	39	86							
x_{12}	29	65	56						
x_{14}	39	85	73	55					
x_{15}	43	92	79	60	92				
x_{16}	40	86	74	56	92	93			
x_{35}	35	76	65	49	84	82	81		
x_{37}	22	48	42	31	51	52	50	54	
x_{65}	−46	−93	−84	−64	−94	−96	−94	−86	−64
	x_7	x_9	x_{11}	x_{12}	x_{14}	x_{15}	x_{16}	x_{35}	x_{37}

D_s^+ BRANCHING RATIOS

A few older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(K^- \text{anything})/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.13^{+0.14}_{-0.12} \pm 0.02$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$[\Gamma(\overline{K}^0 \text{anything}) + \Gamma(K^0 \text{anything})]/\Gamma_{\text{total}}$ **Γ_2/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.39^{+0.28}_{-0.27} \pm 0.04$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^+ \text{anything})/\Gamma_{\text{total}}$ **Γ_3/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.20^{+0.18}_{-0.13} \pm 0.04$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(\text{non-}K\overline{K} \text{anything})/\Gamma_{\text{total}}$ **Γ_4/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.64 \pm 0.17 \pm 0.03$	[4] COFFMAN	91	MRK3	e^+e^- 4.14 GeV

[4] COFFMAN 91 uses the direct measurements of the kaon content to determine this non-$K\overline{K}$ fraction. This number implies that a large fraction of D_s^+ decays involve η, η', and/or non-spectator decays.

$\Gamma(e^+ \text{anything})/\Gamma_{\text{total}}$ **Γ_5/Γ**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.077^{+0.057+0.024}_{-0.043-0.021}$		BAI	97	BES	$e^+e^- \rightarrow D_s^+ D_s^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.20	90	[5] BAI	90	MRK3	e^+e^- 4.14 GeV

[5] Expressed as a value, the BAI 90 result is $\Gamma(e^+ \text{anything})/\Gamma_{\text{total}} = 0.05 \pm 0.05 \pm 0.02$.

$\Gamma(\phi \text{anything})/\Gamma_{\text{total}}$ **Γ_6/Γ**

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.178^{+0.151+0.006}_{-0.072-0.063}$	3	BAI	98	BES	$e^+e^- \rightarrow D_s^+ D_s^-$

Leptonic and semileptonic modes

$\Gamma(\mu^+\nu_\mu)/\Gamma_{\text{total}}$ **Γ_7/Γ**

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^{\pm}$.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.015^{+0.013}_{-0.006}{}^{+0.003}_{-0.002}$	3	[6] BAI	95	BES	$e^+e^- \rightarrow D_s^+ D_s^-$
$0.004^{+0.0018+0.0020}_{-0.0014-0.0019}$	8	[7] AOKI	93	WA75	π^- emulsion 350 GeV
<0.03	0	[8] AUBERT	83	SPEC	μ^+ Fe, 250 GeV

[6] BAI 95 uses one actual $D_s^+ \rightarrow \mu^+\nu_\mu$ event together with two $D_s^+ \rightarrow \tau^+\nu_\tau$ events and assumes μ-τ universality. This value of $\Gamma(\mu^+\nu_\mu)/\Gamma_{\text{total}}$ gives a pseudoscalar decay constant of $(430^{+150}_{-130} \pm 40)$ MeV.

[7] AOKI 93 assumes the ratio of production cross sections of the D_s^+ and D^0 is 0.27. The value of $\Gamma(\mu^+\nu_\mu)/\Gamma_{\text{total}}$ gives a pseudoscalar decay constant $f_{D_s} = (232 \pm 45 \pm 52)$ MeV.

[8] AUBERT 83 assume that the $D_s^{\pm}$ production rate is 20% of total charm production rate.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ Γ_7/Γ_{15}

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^\pm$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.11 ±0.06 OUR FIT	Error includes scale factor of 1.6.			
0.245±0.052±0.074	39	[9] ACOSTA 94	CLE2	$e^+e^- \approx \Upsilon(4S)$

[9] ACOSTA 94 obtains $f_{D_s} = (344 \pm 37 \pm 52 \pm 42)$ MeV from this measurement, using $\Gamma(D_s^+ \to \phi\pi^+)/\Gamma(\text{total}) = 0.037 \pm 0.009$.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\phi\ell^+\nu_\ell)$ Γ_7/Γ_9

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^\pm$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.20±0.10 OUR FIT	Error includes scale factor of 1.6.			
0.16±0.06±0.03	23	[10] KODAMA 96	E653	π^- emulsion, 600 GeV

[10] KODAMA 96 obtains $f_{D_s} = (194 \pm 35 \pm 20 \pm 14)$ MeV from this measurement, using $\Gamma(D_s^+ \to \phi\ell^+\nu)/\Gamma_{\text{total}} = 0.0188 \pm 0.0029$. The third error is from the uncertainty on $\phi\ell^+\nu_\ell$ branching fraction.

$\Gamma(\tau^+\nu_\tau)/\Gamma_{\text{total}}$ Γ_8/Γ

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^\pm$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.074±0.028±0.024	16	[11] ACCIARRI 97F	L3	$D_s^{*+} \to \gamma D_s^+$

[11] The second ACCIARRI 97F error here combines in quadrature systematic (0.016) and normalization (0.018) errors. The branching fraction gives $f_{D_s} = (309 \pm 58 \pm 33 \pm 38)$ MeV.

$\Gamma(\phi\ell^+\nu_\ell)/\Gamma(\phi\pi^+)$ Γ_9/Γ_{15}

For now, we average together measurements of the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ and $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratios. See the end of the D_s^+ Listings for measurements of $D_s^+ \to \phi\ell^+\nu_\ell$ form-factor ratios.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.55±0.06 OUR FIT				
0.54±0.05 OUR AVERAGE				
0.54±0.05±0.04	367	[12] BUTLER 94	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.58±0.17±0.07	97	[13] FRABETTI 93G	E687	γ Be $\overline{E}_\gamma$= 220 GeV
0.57±0.15±0.15	104	[14] ALBRECHT 91	ARG	$e^+e^- \approx$ 10.4 GeV
$0.49\pm0.10^{+0.10}_{-0.14}$	54	[15] ALEXANDER 90B	CLEO	e^+e^- 10.5–11 GeV

[12] BUTLER 94 uses both $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ events, and makes a phase-space adjustment to the latter to use them as $\phi e^+\nu_e$ events.

[13] FRABETTI 93G measures the $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratio.

[14] ALBRECHT 91 measures the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ ratio.

[15] ALEXANDER 90B measures an average of the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ and $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratios.

$\Gamma(\eta\ell^+\nu_\ell)/\Gamma(\phi\ell^+\nu_\ell)$ Γ_{11}/Γ_9

Unseen decay modes of the η and the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.27±0.19 OUR FIT				
1.24±0.12±0.15	440	[16] BRANDENB... 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

[16] BRANDENBURG 95 uses both e^+ and μ^+ events and makes a phase-space adjustment to use the μ^+ events as e^+ events.

$\Gamma(\eta'(958)\ell^+\nu_\ell)/\Gamma(\phi\ell^+\nu_\ell)$ Γ_{12}/Γ_9

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.44±0.13 OUR FIT					
0.43±0.11±0.07		29	[17] BRANDENB... 95	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90		[18] KODAMA 93B	E653	π^- emulsion 600 GeV

[17] BRANDENBURG 95 uses both e^+ and μ^+ events and makes a phase-space adjustment to use the μ^+ events as e^+ events.

[18] KODAMA 93B uses μ^+ events.

$[\Gamma(\eta\ell^+\nu_\ell) + \Gamma(\eta'(958)\ell^+\nu_\ell)]/\Gamma(\phi\ell^+\nu_\ell)$ $\Gamma_{10}/\Gamma_9 = (\Gamma_{11}+\Gamma_{12})/\Gamma_9$

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.72±0.23 OUR FIT				
3.9 ±1.6	13	[19] KODAMA 93	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.67±0.17±0.17		[20] BRANDENB... 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

[19] KODAMA 93 uses μ^+ events.

[20] This BRANDENBURG 95 data is redundant with data in previous blocks.

Hadronic modes with a $K\overline{K}$ pair.

$\Gamma(K^+\overline{K}^0)/\Gamma(\phi\pi^+)$ Γ_{13}/Γ_{15}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.01±0.16 OUR AVERAGE				
1.15±0.31±0.19	68	ANJOS 90C	E691	γ Be
0.92±0.32±0.20		ADLER 89B	MRK3	e^+e^- 4.14 GeV
0.99±0.17±0.10		CHEN 89	CLEO	e^+e^- 10 GeV

$\Gamma(\phi\pi^+)/\Gamma_{\text{total}}$ Γ_{15}/Γ

We now have model-independent measurements of this branching fraction, and so we no longer use the earlier, model-dependent results. See the "Note on D Mesons" in the D^+ Listings for a discussion.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.036 ±0.009 OUR FIT					
0.036 ±0.009 OUR AVERAGE					
0.0359±0.0077±0.0048			[21] ARTUSO 96	CLE2	e^+e^- at $\Upsilon(4S)$
$0.039\ ^{+0.051}_{-0.019}\ ^{+0.018}_{-0.011}$			[22] BAI 95C	BES	e^+e^- 4.03 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.051 ±0.004 ±0.008			[23] BUTLER 94	CLE2	$e^+e^- \approx \Upsilon(4S)$
<0.048	90		MUHEIM 94		
0.046 ±0.015			[24] MUHEIM 94		
0.031 ±0.009			[24] MUHEIM 94		
0.031 ±0.009 ±0.006			[23] FRABETTI 93G	E687	γ Be $\overline{E}_\gamma$= 220 GeV
0.024 ±0.010			[23] ALBRECHT 91	ARG	$e^+e^- \approx$ 10.4 GeV
<0.041	90	0	[22] ADLER 90B	MRK3	e^+e^- 4.14 GeV
$0.031\ \pm0.006\ ^{+0.011}_{-0.009}$			[23] ALEXANDER 90B	CLEO	e^+e^- 10.5–11 GeV
0.048 ±0.017 ±0.019			[25] ALVAREZ 90C	NA14	Photoproduction
>0.034	90		[23] ANJOS 90B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV
0.02 ±0.01		405	[26] CHEN 89	CLEO	e^+e^- 10 GeV
0.033 ±0.016 ±0.010		9	[26] BRAUNSCH... 87	TASS	e^+e^- 35–44 GeV
0.033 ±0.011		30	[26] DERRICK 85B	HRS	e^+e^- 29 GeV

[21] ARTUSO 96 uses partially reconstructed $\overline{B}^0 \to D^{*+}D_s^{*-}$ decays to get a model-independent value for $\Gamma(D_s^- \to \phi\pi^-)/\Gamma(D^0 \to K^-\pi^+)$ of 0.92 ± 0.20 ± 0.11.

[22] BAI 95C uses $e^+e^- \to D_s^+D_s^-$ events in which one or both of the $D_s^\pm$ are observed to obtain the first model-independent measurement of the $D_s^+ \to \phi\pi^+$ branching fraction, without assumptions about $\sigma(D_s^\pm)$. However, with only two "doubly-tagged" events, the statistical error is too large for the result to be competitive with indirect measurements. ADLER 90B used the same method to set a limit.

[23] BUTLER 94, FRABETTI 93G, ALBRECHT 91, ALEXANDER 90B, and ANJOS 90B measure the ratio $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D_s^+ \to \phi\pi^+)$, where $\ell = e$ and/or μ, and then use a theoretical calculation of the ratio of widths $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D^+ \to \overline{K}^{*0}\ell^+\nu)$. Not everyone uses the same value for this ratio.

[24] The two MUHEIM 94 values here are model-dependent calculations based on distinct data sets. The first uses measurements of the $D_2^*(2460)^0$ and $D_{s1}(2536)^+$, the second uses B-decay factorization and $\Gamma(D_s^+ \to \mu^+\nu_\mu)/\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)$. A third calculation using the semileptonic width of $D_s^+ \to \phi\ell^+\nu_\ell$ is not independent of other results listed here. Note also the upper limit, based on the sum of established D_s^+ branching ratios.

[25] ALVAREZ 90C relies on the Lund model to estimate the ratio of D_s^+ to D^+ cross sections.

[26] Values based on crude estimates of the $D_s^\pm$ production level. DERRICK 85B errors are statistical only.

$\Gamma(\phi\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{15}/Γ_{14}

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.82 ±0.08 OUR FIT			
0.807±0.067±0.096	FRABETTI 95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(K^+K^-\pi^+)$ Γ_{16}/Γ_{14}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.75 ±0.07 OUR FIT			
0.717±0.069±0.060	FRABETTI 95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ Γ_{16}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.92±0.09 OUR FIT				
0.95±0.10 OUR AVERAGE				
0.85±0.34±0.20	9	ALVAREZ 90C	NA14	Photoproduction
0.84±0.30±0.22		ADLER 89B	MRK3	e^+e^- 4.14 GeV
1.05±0.17±0.12		CHEN 89	CLEO	e^+e^- 10 GeV
0.87±0.13±0.05	117	ANJOS 88	E691	Photoproduction
1.44±0.37	87	ALBRECHT 87F	ARG	e^+e^- 10 GeV

$\Gamma(f_0(980)\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{17}/Γ_{14}

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.40±0.16 OUR FIT	Error includes scale factor of 2.3.		
1.00±0.32±0.24	FRABETTI 95B	E687	Dalitz plot analysis

$\Gamma(f_J(1710)\pi^+ \to K^+K^-\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{19}/Γ_{14}

This includes *only* K^+K^- decays of the $f_J(1710)$, because branching fractions of this resonance are not known.

VALUE	DOCUMENT ID	TECN	COMMENT
0.034±0.023±0.035	FRABETTI 95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}_0^*(1430)^0)/\Gamma(K^+K^-\pi^+)$ Γ_{18}/Γ_{14}

Unseen decay modes of the $\overline{K}_0^*(1430)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.150±0.062±0.062	FRABETTI 95B	E687	Dalitz plot analysis

$\Gamma(K^+K^-\pi^+\text{nonresonant})/\Gamma(\phi\pi^+)$ Γ_{20}/Γ_{15}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.07±0.05	48	ANJOS	88	E691	Photoproduction

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\phi\pi^+)$ Γ_{22}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.20±0.21±0.13	CHEN	89	CLEO	e^+e^- 10 GeV

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(K^+\overline{K}^0)$ Γ_{22}/Γ_{13}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	90	FRABETTI	95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma(\phi\pi^+)$ Γ_{24}/Γ_{15}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±1.0±0.5		11	ANJOS	89E	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.6	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(\phi\pi^+)$ Γ_{25}/Γ_{15}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.86\pm0.26^{+0.29}_{-0.40}$	253	AVERY	92	CLE2	$e^+e^- \simeq$ 10.5 GeV

$\Gamma(\phi\pi^+\pi^0\,\text{3-body})/\Gamma(\phi\pi^+)$ Γ_{26}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.71	90	DAOUDI	92	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0\,\text{non-}\phi)/\Gamma(\phi\pi^+)$ Γ_{27}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4	90	[27] ANJOS	89E	E691	Photoproduction

[27] Total minus ϕ component.

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_{28}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.77	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+)/\Gamma(\phi\pi^+)$ Γ_{29}/Γ_{15}

VALUE	DOCUMENT ID		TECN	COMMENT
1.2 ±0.2 ±0.2	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^*(892)^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ Γ_{30}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.6±0.4±0.4	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+\,\text{non-}K^{*+}\overline{K}^{*0})/\Gamma(\phi\pi^+)$ Γ_{31}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.80	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^+K^-\pi^+\pi^+\pi^-)/\Gamma(K^+K^-\pi^+)$ Γ_{32}/Γ_{14}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.188±0.036±0.040	75	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_{33}/Γ_{15}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.33±0.06 OUR AVERAGE						
0.28±0.06±0.01		40	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV
0.58±0.21±0.10		21	FRABETTI	92	E687	γBe
0.42±0.13±0.07		19	ANJOS	88	E691	Photoproduction
1.11±0.37±0.28		62	ALBRECHT	85D	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.24	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(K^+K^-\pi^+\pi^+\pi^-\,\text{non-}\phi)/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.003\ ^{+0.003}_{-0.002}$	BARLAG	92C	ACCM	π^- 230 GeV

$\Gamma(K^+K^-\pi^+\pi^+\pi^-\,\text{non-}\phi)/\Gamma(\phi\pi^+)$ Γ_{34}/Γ_{15}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.32	90	10	ANJOS	88	E691	Photoproduction

Hadronic modes without K's

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(K^+K^-\pi^+)$ Γ_{35}/Γ_{14}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.23 ±0.04 OUR FIT	Error includes scale factor of 1.2.				
0.265±0.041±0.031	98	FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_{35}/Γ_{15}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.28±0.06 OUR FIT	Error includes scale factor of 1.3.				
0.39±0.08 OUR AVERAGE					
0.33±0.10±0.04	29	ADAMOVICH	93	WA82	π^- 340 GeV
0.44±0.10±0.04		ANJOS	89	E691	Photoproduction

$\Gamma(\rho^0\pi^+)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{36}/Γ_{35}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.073	90	FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

$\Gamma(\rho^0\pi^+)/\Gamma(\phi\pi^+)$ Γ_{36}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.08	90	ANJOS	89	E691	Photoproduction
<0.22	90	ALBRECHT	87G	ARG	e^+e^- 10 GeV

$\Gamma(f_0(980)\pi^+)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{37}/Γ_{35}

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.7 ±0.6 OUR FIT	Error includes scale factor of 2.4.			
2.06±0.27±0.08	FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

$\Gamma(f_0(980)\pi^+)/\Gamma(\phi\pi^+)$ Γ_{37}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.49±0.20 OUR FIT	Error includes scale factor of 2.6.			
0.28±0.10±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(f_2(1270)\pi^+)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{38}/Γ_{35}

Unseen decay modes of the $f_2(1270)$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.10±0.03	FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

$\Gamma(f_0(1500)\pi^+ \to \pi^+\pi^-\pi^+)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{39}/Γ_{35}

This includes only $\pi^+\pi^-$ decays of the $f_0(1500)$, because branching fractions of this resonance are not known.

VALUE	DOCUMENT ID		TECN	COMMENT
0.274±0.114±0.019	[28] FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

[28] FRABETTI 97D calls this mode $S(1475)\pi^+$, but finds the mass and width of this $S(1475)$ to be in excellent agreement with those of the $f_0(1500)$.

$\Gamma(\pi^+\pi^+\pi^-\,\text{nonresonant})/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{40}/Γ_{35}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.269	90	[29] FRABETTI	97D	E687	γ Be $\approx$ 200 GeV

[29] We rather arbitrarily use this FRABETTI 97D limit instead of the much large ANJOS 89 value given in the next entry. See, however, FRABETTI 97D on the difficulty of distengangling the $f_0(1500)\pi^+$ and nonresonant modes.

$\Gamma(\pi^+\pi^+\pi^-\,\text{nonresonant})/\Gamma(\phi\pi^+)$ Γ_{40}/Γ_{15}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29±0.09±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\phi\pi^+)$ Γ_{41}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.3	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$ Γ_{42}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.09±0.06		165	ALEXANDER	92	CLE2	$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(\phi\pi^+)$ Γ_{43}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(\eta\pi^+)$ Γ_{43}/Γ_{42}

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.04±0.03	BALEST	97	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^+K^-\pi^+)$ Γ_{44}/Γ_{14}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.158±0.042±0.031	37	FRABETTI	97C	E687	γBe, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(\phi\pi^+)$ Γ_{44}/Γ_{15}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	90	ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(\phi\pi^+)$ Γ_{46}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$2.86\pm0.38^{+0.36}_{-0.38}$	217	AVERY 92	CLE2	$\eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0$

$\Gamma(\eta\pi^+\pi^0\text{3-body})/\Gamma(\phi\pi^+)$ Γ_{47}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.82	90	DAOUDI 92	CLE2	$e^+e^- \approx$ 10.5 GeV

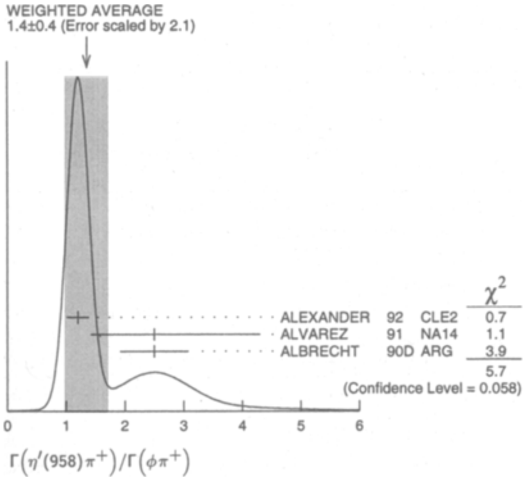
$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.049^{+0.033}_{-0.030}$	BARLAG 92C	ACCM	π^- 230 GeV

$\Gamma(\eta'(958)\pi^+)/\Gamma(\phi\pi^+)$ Γ_{49}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
1.4 ± 0.4 OUR AVERAGE			Error includes scale factor of 2.1. See the ideogram below.		
$1.20\pm0.15\pm0.11$		281	ALEXANDER 92	CLE2	$\eta' \rightarrow \eta\pi^+\pi^-$, $\rho^0\gamma$
$2.5 \pm1.0 {}^{+1.5}_{-0.4}$		22	ALVAREZ 91	NA14	Photoproduction
$2.5 \pm0.5 \pm0.3$		215	ALBRECHT 90D	ARG	$e^+e^- \approx$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.3	90		ANJOS 91B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV



$\Gamma(\eta'(958)\rho^+)/\Gamma(\phi\pi^+)$ Γ_{51}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$3.44\pm0.62^{+0.44}_{-0.46}$	68	AVERY 92	CLE2	$\eta' \rightarrow \eta\pi^+\pi^-$

$\Gamma(\eta'(958)\pi^+\pi^0\text{3-body})/\Gamma(\phi\pi^+)$ Γ_{52}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.85	90	DAOUDI 92	CLE2	$e^+e^- \approx$ 10.5 GeV

Modes with one or three K's

$\Gamma(K^0\pi^+)/\Gamma(\phi\pi^+)$ Γ_{53}/Γ_{15}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.21	90	ADLER 89B	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^0\pi^+)/\Gamma(K^+\overline{K}^0)$ Γ_{53}/Γ_{13}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.53	90	FRABETTI 95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_{54}/Γ_{15}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.28\pm0.06\pm0.05$	85	FRABETTI 95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+\rho^0)/\Gamma(\phi\pi^+)$ Γ_{55}/Γ_{15}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.08	90	FRABETTI 95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^*(892)^0\pi^+)/\Gamma(\phi\pi^+)$ Γ_{56}/Γ_{15}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.18\pm0.05\pm0.04$	25	FRABETTI 95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+K^+K^-)/\Gamma(\phi\pi^+)$ Γ_{57}/Γ_{15}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.016	90	FRABETTI 95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV

$\Gamma(\phi K^+)/\Gamma(\phi\pi^+)$ Γ_{58}/Γ_{15}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.013	90	FRABETTI 95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.071	90	ANJOS 92D	E691	γBe, $\overline{E}_\gamma$ = 145 GeV

Rare or forbidden modes

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{59}/Γ

This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<4.3 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{60}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<5.9 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^*(892)^+\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{61}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-3}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$ Γ_{62}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<4.3 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^-\mu^+\mu^+)/\Gamma_{\text{total}}$ Γ_{63}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<5.9 \times 10^{-4}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$\Gamma(K^*(892)^-\mu^+\mu^+)/\Gamma_{\text{total}}$ Γ_{64}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-3}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV

$D_s^+ \rightarrow \phi\ell^+\nu_\ell$ FORM FACTORS

$r_2 \equiv A_2(0)/A_1(0)$ in $D_s^+ \rightarrow \phi\ell^+\nu_\ell$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.6 ± 0.4 OUR AVERAGE				
$1.4\pm0.5\pm0.3$	308	[30] AVERY 94B	CLE2	e^+e^- 10 GeV
$1.1\pm0.8\pm0.1$	90	[31] FRABETTI 94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$2.1^{+0.6}_{-0.5}\pm0.2$	19	[31] KODAMA 93	E653	600 GeV $\pi^- N$

[30] AVERY 94B uses $D_s^+ \rightarrow \phi e^+\nu_e$ decays.

[31] FRABETTI 94F and KODAMA 93 use $D_s^+ \rightarrow \phi\mu^+\nu_\mu$ decays.

$r_V \equiv V(0)/A_1(0)$ in $D_s^+ \rightarrow \phi\ell^+\nu_\ell$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.5 ± 0.5 OUR AVERAGE				
$0.9\pm0.6\pm0.3$	308	[32] AVERY 94B	CLE2	e^+e^- 10 GeV
$1.8\pm0.9\pm0.2$	90	[33] FRABETTI 94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$2.3^{+1.1}_{-0.9}\pm0.4$	19	[33] KODAMA 93	E653	600 GeV $\pi^- N$

[32] AVERY 94B uses $D_s^+ \rightarrow \phi e^+\nu_e$ decays.

[33] FRABETTI 94F and KODAMA 93 use $D_s^+ \rightarrow \phi\mu^+\nu_\mu$ decays.

Γ_L/Γ_T in $D_s^+ \rightarrow \phi\ell^+\nu_\ell$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.72 ± 0.18 OUR AVERAGE				
$1.0 \pm0.3 \pm0.2$	308	[34] AVERY 94B	CLE2	e^+e^- 10 GeV
$1.0 \pm0.5 \pm0.1$	90	[35] FRABETTI 94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$0.54\pm0.21\pm0.10$	19	[35] KODAMA 93	E653	600 GeV $\pi^- N$

[34] AVERY 94B uses $D_s^+ \rightarrow \phi e^+\nu_e$ decays.

[35] FRABETTI 94F and KODAMA 93 use $D_s^+ \rightarrow \phi\mu^+\nu_\mu$ decays. Γ_L/Γ_T is evaluated for a lepton mass of zero.

$D_s^\pm$ REFERENCES

BAI	98	PR D57 28	+Bardon, Blum+	(BEPC BES Collab.)
ACCIARRI	97F	PL B396 327	M. Acciarri+	(L3 Collab.)
BAI	97	PR D56 3779	+Bardon, Bian, Blum+	(BEPC BES Collab.)
BALEST	97	PRL 79 1436	+Behrens, Cho, Ford+	(CLEO Collab.)
FRABETTI	97C	PL B401 131	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	97D	PL B407 79	+Cheung, Cumalat+	(FNAL E687 Collab.)
ARTUSO	96	PL B378 364	+Efimov, Gao, Goldberg+	(CLEO Collab.)
KODAMA	96	PL B382 299	+Torikai, Ushida+	(FNAL E653 Collab.)
BAI	95	PRL 74 4599	+Bardon, Blum, Breakstone+	(BES Collab.)
BAI	95C	PR D52 3781	+Bardon, Blum, Breakstone+	(BES Collab.)
BRANDENB...	95	PRL 75 3804	Brandenburg, Cinabro, Liu+	(CLEO Collab.)
FRABETTI	95	PL B346 199	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95B	PL B351 591	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95E	PL B359 403	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95F	PL B363 259	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ACOSTA	94	PR D49 5690	+Athanas, Masek, Paar+	(CLEO Collab.)
AVERY	94B	PL B337 405	+Freyberger, Rodriguez+	(CLEO Collab.)
BROWN	94	PR D50 1884	+Fast, McIlwain, Miao+	(CLEO Collab.)
BUTLER	94	PL B324 255	+Fu, Kalbfleisch, Ross+	(CLEO Collab.)
FRABETTI	94F	PL B328 187	+Cheung, Cumalat+	(FNAL E687 Collab.)
MUHEIM	94	PR D49 3767	+Stone	(SYRA)
ADAMOVICH	93	PL B305 177	+Alexandrov, Antinori+	(CERN WA82 Collab.)
AOKI	93	PTP 89 131	+Baroni, Bisi, Breslin+	(CERN WA75 Collab.)
FRABETTI	93F	PRL 71 827	+Cheung, Cumalat, Dallapiccola+	(FNAL E687 Collab.)
FRABETTI	93G	PL B313 253	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	93	PL B309 483	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
KODAMA	93B	PL B313 260	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	92B	ZPHY C53 361	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALEXANDER	92	PRL 68 1275	+Bebek, Berkelman, Besson+	(CLEO Collab.)
ANJOS	92D	PRL 69 2892	+Appel, Bean, Bediaga+	(FNAL E691 Collab.)
AVERY	92	PRL 68 1279	+Freyberger, Rodriguez, Yelton+	(CLEO Collab.)
BARLAG	92C	ZPHY C55 383	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
Also	90D	ZPHY C48 29	Barlag, Becker, Boehringer, Bosman+	(ACCMOR Collab.)
DAOUDI	92	PR D45 3965	+Ford, Johnson, Lingel+	(CLEO Collab.)
FRABETTI	92	PL B281 167	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
ALBRECHT	91	PL B255 634	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALVAREZ	91	PL B255 639	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	91B	PR D43 R2063	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
COFFMAN	91	PL B263 135	+DeJongh, Dubois, Eigen, Hitlin+	(Mark III Collab.)
ADLER	90B	PRL 64 169	+Bai, Blaylock, Bolton+	(Mark III Collab.)
ALBRECHT	90D	PL B245 315	+Ehrlichmann, Glaeser, Harder+	(ARGUS Collab.)
ALEXANDER	90B	PRL 65 1531	+Artuso, Bebek, Berkelman+	(CLEO Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	90C	PL B246 261	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90B	PRL 64 2885	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	90C	PR D41 2705	+Appel, Bean+	(FNAL E691 Collab.)
BAI	90	PRL 65 686	+Blaylock, Bolton, Brient+	(Mark III Collab.)
BARLAG	90C	ZPHY C46 563	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
FRABETTI	90	PL B251 639	+Bogart, Cheung, Coteus+	(FNAL E687 Collab.)
ADLER	89B	PRL 63 1211	+Bai, Becker, Blaylock, Bolton+	(Mark III Collab.)
Also	89D	PRL 63 2858 erratum		
ANJOS	89	PRL 62 125	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	89E	PL B223 267	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
CHEN	89	PL B226 192	+McIlwain, Miller, Ng, Shibata+	(CLEO Collab.)
ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88	PRL 60 897	+Appel+	(FNAL E691 Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL E691 Collab.)
ALBRECHT	87F	PL B179 398	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	87G	PL B195 102	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ANJOS	87B	PRL 58 1818	+Appel, Bracker, Browder+	(FNAL E691 Collab.)
BECKER	87B	PL B184 277	+Boehringer, Bosman+	(NA11 and NA32 Collab.)
BLAYLOCK	87	PRL 58 2171	+Bolton, Brown, Bunnell+	(Mark III Collab.)
BRAUNSCH...	87	ZPHY C35 317	Braunschweig, Gerhards+	(TASSO Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
JUNG	86	PRL 56 1775	+Abachi+	(HRS Collab.)
USHIDA	86	PRL 56 1767	+Kondo, Tasaka, Park+	(FNAL E531 Collab.)
ALBRECHT	85D	PL 153B 343	+Drescher, Binder, Drews+	(ARGUS Collab.)
DERRICK	85B	PRL 54 2568	+Fernandez, Fries, Hyman+	(HRS Collab.)
AIHARA	84D	PRL 53 2465	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALTHOFF	84	PL 136B 130	+Braunschweig, Kirschfink+	(TASSO Collab.)
BAILEY	84	PL 139B 320	+Belau, Bohringer, Bosman+	(ACCMOR Collab.)
AUBERT	83	NP B213 31	+Bassompierre, Becks, Best+	(EMC Collab.)
CHEN	83C	PRL 51 634	+Alam, Giles, Kagan+	(CLEO Collab.)
USHIDA	83	PRL 51 2362	+Kondo, Fujioka, Fukushima+	(FNAL E653 Collab.)

OTHER RELATED PAPERS

RICHMAN	95	RMP 67 893	+Burchat	(UCSB, STAN)

$D_s^{*\pm}$

$I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-.

$D_s^{*\pm}$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2112.4±0.7 OUR FIT Error includes scale factor of 1.1.			
2106.6±2.1±2.7	[1] BLAYLOCK 87	MRK3	$e^+e^- \to D_s^\pm \gamma X$

[1] Assuming $D_s^\pm$ mass = 1968.7 ± 0.9 MeV.

$m_{D_s^{*\pm}} - m_{D_s^\pm}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
143.8 ± 0.4 OUR FIT				
143.9 ± 0.4 OUR AVERAGE				
143.76± 0.39±0.40		GRONBERG 95	CLE2	e^+e^-
144.22± 0.47±0.37		BROWN 94	CLE2	e^+e^-
142.5 ± 0.8 ±1.5		[2] ALBRECHT 88	ARG	$e^+e^- \to D_s^\pm \gamma X$
139.5 ± 8.3 ±9.7	60	AIHARA 84D	TPC	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
143.0 ±18.0	8	ASRATYAN 85	HLBC	FNAL 15-ft, ν-^{2}H
110 ±46		BRANDELIK 79	DASP	$e^+e^- \to D_s^\pm \gamma X$

[2] Result includes data of ALBRECHT 84B.

$D_s^{*\pm}$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 1.9	90	GRONBERG 95	CLE2	e^+e^-
< 4.5	90	ALBRECHT 88	ARG	$E_{\rm cm}^{ee}$ = 10.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.9	90	BROWN 94	CLE2	e^+e^-
<22	90	BLAYLOCK 87	MRK3	$e^+e^- \to D_s^\pm \gamma X$

D_s^{*+} DECAY MODES

D_s^{*-} modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D_s^+\gamma$	(94.2±2.5) %
Γ_2	$D_s^+\pi^0$	(5.8±2.5) %

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 1 measurements and one constraint to determine 2 parameters. The overall fit has a χ^2 = 0.0 for 0 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{r|l} x_2 & -100 \\ \hline & x_1 \end{array}$$

D_s^{*+} BRANCHING RATIOS

$\Gamma(D_s^+\gamma)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.942±0.026 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	ASRATYAN 91	HLBC	$\overline{\nu}_\mu$Ne
seen	ALBRECHT 88	ARG	$e^+e^- \to D_s^\pm \gamma X$
seen	AIHARA 84D		
seen	ALBRECHT 84B		
seen	BRANDELIK 79		

$\Gamma(D_s^+\pi^0)/\Gamma(D_s^+\gamma)$ Γ_2/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.062±0.029 OUR FIT			
$0.062^{+0.020}_{-0.018}$±0.022	GRONBERG 95	CLE2	e^+e^-

$D_s^{*\pm}$ REFERENCES

GRONBERG	95	PRL 75 3232	+Korte, Kutschke+	(CLEO Collab.)
BROWN	94	PR D50 1884	+Fast, McIlwain, Miao+	(CLEO Collab.)
ASRATYAN	91	PL B257 525	+Marage+(ITEP, BELG, SACL, SERP, CRAC, BARI, CERN)	
ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
BLAYLOCK	87	PRL 58 2171	+Bolton, Brown, Bunnell+	(Mark III Collab.)
ASRATYAN	85	PL 156B 441	+Fedotov, Ammosov, Burtovoy+	(ITEP, SERP)
AIHARA	84D	PRL 53 2465	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALBRECHT	84B	PL 146B 111	+Drescher, Heller+	(ARGUS Collab.)
BRANDELIK	79	PL 80B 412	+Braunschweig, Martyn, Sander+	(DASP Collab.)

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
BRANDELIK	78C	PL 76B 361	+Cords+	(DASP Collab.)
BRANDELIK	77B	PL 70B 132	+Braunschweig, Martyn, Sander+	(DASP Collab.)

$D_{s1}(2536)^{\pm}$

$I(J^P) = 0(1^+)$
J, P need confirmation.

Seen in $D^*(2010)^+ K^0$. Not seen in $D^+ K^0$ or $D^0 K^+$. $J^P = 1^+$ assignment strongly favored.

$D_{s1}(2536)^{\pm}$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2535.35± 0.34±0.5 OUR EVALUATION					
2535.35± 0.34 OUR AVERAGE					
2534.2 ± 1.2	9	ASRATYAN	94	BEBC	$\nu N \rightarrow D^* K^0 X, D^{*0} K^{\pm} X$
2535 ± 0.6 ±1	75	FRABETTI	94B	E687	$\gamma \mathrm{Be} \rightarrow D^{*+} K^0 X, D^{*0} K^+ X$
2535.3 ± 0.2 ±0.5	134	ALEXANDER	93	CLE2	$e^+ e^- \rightarrow D^{*0} K^+ X$
2534.8 ± 0.6 ±0.6	44	ALEXANDER	93	CLE2	$e^+ e^- \rightarrow D^{*+} K^0 X$
2535.2 ± 0.5 ±1.5	28	ALBRECHT	92R	ARG	$10.4\ e^+ e^- \rightarrow D^{*0} K^+ X$
2536.6 ± 0.7 ±0.4		AVERY	90	CLEO	$e^+ e^- \rightarrow D^{*+} K^0 X$
2535.9 ± 0.6 ±2.0		ALBRECHT	89E	ARG	$D^*_{s1} \rightarrow D^*(2010) K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2535 ±28		[1] ASRATYAN	88	HLBC	$\nu N \rightarrow D_s \gamma \gamma X$

[1] Not seen in $D^* K$.

$m_{D_{s1}(2536)^{\pm}} - m_{D^*_s(2111)}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
424±28	ASRATYAN	88	HLBC	$D^{*\pm}_s \gamma$

$D_{s1}(2536)^{\pm}$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2.3	90		ALEXANDER	93	CLEO	$e^+ e^- \rightarrow D^{*0} K^+ X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.2	90	75	FRABETTI	94B	E687	$\gamma \mathrm{Be} \rightarrow D^{*+} K^0 X, D^{*0} K^+ X$
<3.9	90		ALBRECHT	92R	ARG	$10.4\ e^+ e^- \rightarrow D^{*0} K^+ X$
<5.44	90		AVERY	90	CLEO	$e^+ e^- \rightarrow D^{*+} K^0 X$
<4.6	90		ALBRECHT	89E	ARG	$D^*_{s1} \rightarrow D^*(2010) K^0$

$D_{s1}(2536)^{+}$ DECAY MODES

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+ K^0$	seen
Γ_2	$D^*(2007)^0 K^+$	seen
Γ_3	$D^+ K^0$	not seen
Γ_4	$D^0 K^+$	not seen
Γ_5	$D^{*+}_s \gamma$	possibly seen

$D_{s1}(2536)^{+}$ BRANCHING RATIOS

$\Gamma(D^+ K^0)/\Gamma(D^*(2010)^+ K^0)$ — Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.40	90	ALEXANDER	93	CLEO	$e^+ e^- \rightarrow D^{*+} K^0 X$
<0.43	90	ALBRECHT	89E	ARG	$D^*_{s1} \rightarrow D^*(2010) K^0$

$\Gamma(D^{*+}_s \gamma)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
possibly seen	ASRATYAN	88	HLBC	$\nu N \rightarrow D_s \gamma \gamma X$

$\Gamma(D^0 K^+)/\Gamma(D^*(2007)^0 K^+)$ — Γ_4/Γ_2

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.12	90	ALEXANDER	93	CLEO	$e^+ e^- \rightarrow D^{*0} K^+ X$

$\Gamma(D^{*+}_s \gamma)/\Gamma(D^*(2007)^0 K^+)$ — Γ_5/Γ_2

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.42	90	ALEXANDER	93	CLEO	$e^+ e^- \rightarrow D^{*0} K^+ X$

$\Gamma(D^*(2007)^0 K^+)/\Gamma(D^*(2010)^+ K^0)$ — Γ_2/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.22±0.23 OUR AVERAGE				
1.1 ±0.3	ALEXANDER	93	CLEO	$e^+ e^- \rightarrow D^{*0} K^+ X, D^{*+} K^0 X$
1.4 ±0.3 ±0.2	[2] ALBRECHT	92R	ARG	$10.4\ e^+ e^- \rightarrow D^{*0} K^+ X, D^{*+} K^0 X$

[2] Evaluated by us from published inclusive cross-sections.

$D_{s1}(2536)^{\pm}$ REFERENCES

ASRATYAN	94	ZPHY C 61 563	+Aderholz+	(BIRM, BELG, CERN, SERP, ITEP, RAL)
FRABETTI	94B	PRL 72 324	+Cheung, Cumalat+	(FNAL E687 Collab.)
ALEXANDER	93	PL B303 377	+Bebek+	(CLEO Collab.)
ALBRECHT	92R	PL B297 425	+Ehrlichmann+	(ARGUS Collab.)
AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89E	PL B230 162	+Glaser, Harder+	(ARGUS Collab.)
ASRATYAN	88	ZPHY C40 483	+Fedotov+	(ITEP, SERP)

$D_{sJ}(2573)^{\pm}$

$I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 2^+.

$D_{sJ}(2573)^{\pm}$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2573.5±1.7 OUR AVERAGE						
2574.5±3.3±1.6		ALBRECHT	96	ARG		$e^+ e^- \rightarrow D^0 K^+ X$
$2573.2^{+1.7}_{-1.6}$±0.9	217	KUBOTA	94	CLE2	+	$e^+ e^- \sim$ 10.5 GeV

$D_{sJ}(2573)^{\pm}$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$15\ ^{+5}_{-4}$ OUR AVERAGE						
10.4±8.3±3.0		ALBRECHT	96	ARG		$e^+ e^- \rightarrow D^0 K^+ X$
$16\ ^{+5}_{-4}$ ±3	217	KUBOTA	94	CLE2	+	$e^+ e^- \sim$ 10.5 GeV

$D_{sJ}(2573)^{+}$ DECAY MODES

$D_{sJ}(2573)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0 K^+$	seen
Γ_2	$D^*(2007)^0 K^+$	not seen

$D_{sJ}(2573)^{+}$ BRANCHING RATIOS

$\Gamma(D^0 K^+)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
seen	217	KUBOTA	94	CLE2	±	$e^+ e^- \sim$ 10.5 GeV

$\Gamma(D^*(2007)^0 K^+)/\Gamma(D^0 K^+)$ — Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.33	90	KUBOTA	94	CLE2	+	$e^+ e^- \sim$ 10.5 GeV

$D_{sJ}(2573)^{\pm}$ REFERENCES

ALBRECHT	96	ZPHY C69 405	+Hamacher, Hofmann+	(ARGUS Collab.)
KUBOTA	94	PRL 72 1972	+Lattery, Nelson, Patton+	(CLEO Collab.)

BOTTOM MESONS
$(B = \pm 1)$

$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $\overline{B}^0 = \bar{d}b$, $B^- = \bar{u}b$, similarly for B^*'s

B-particle organization

Many measurements of *B* decays involve admixtures of *B* hadrons. Previously we arbitrarily included such admixtures in the $B^{\pm}$ section, but because of their importance we have created two new sections: "$B^{\pm}/B^0$ Admixture" for $\Upsilon(4S)$ results and "$B^{\pm}/B^0/B^0_s/b$-baryon Admixture" for results at higher energies. Most inclusive decay branching fractions are found in the Admixture sections. B^0-$\overline{B}^0$ mixing data are found in the B^0 section, while B^0_s-$\overline{B}^0_s$ mixing data and B-$\overline{B}$ mixing data for a B^0/B^0_s admixture are found in the B^0_s section. *CP*-violation data are found in the B^0 section. *b*-baryons are found near the end of the Baryon section.

The organization of the *B* sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

[Production and Decay of *b*-flavored Hadrons]
[Semileptonic Decays of *B* Mesons]
- $B^{\pm}$
  - mass, mean life
  - branching fractions
- B^0
  - mass, mean life
  - branching fractions
  - polarization in B^0 decay
  - B^0-$\overline{B}^0$ mixing
  - [B^0-$\overline{B}^0$ Mixing and *CP* Violation in *B* Decay]
  - *CP* violation
- $B^{\pm}$ B^0 Admixture
  - branching fractions
- $B^{\pm}/B^0/B^0_s/b$-baryon Admixture
  - mean life
  - production fractions
  - branching fractions
- B^*
  - mass
- $B^*_J(5732)$
  - mass, width
- B^0_s
  - mass, mean life
  - branching fractions
  - polarizaton in B^0_s decay
  - B^0_s-$\overline{B}^0_s$ mixing
  - B-$\overline{B}$ mixing (admixture of B^0, B^0_s)
- B^*_s
  - mass
- $B^*_{sJ}(5850)$
  - mass, width
- $B^{\pm}_c$
  - mass, mean life
  - branching fractions

At end of Baryon Listings:
- Λ_b
  - mass, mean life
  - branching fractions
- Ξ^0_b, Ξ^-_b
  - mean life
- *b*-baryon Admixture
  - mean life
  - branching fractions

PRODUCTION AND DECAY OF *b*-FLAVORED HADRONS

Written March 1998 by K. Honscheid (Ohio State University, Columbus).

In 1997 we celebrated the 20th anniversary of the discovery of the *b* quark. What started out as a bump in the dimuon invariant mass spectrum has turned into the exciting field of heavy flavor physics. Weak decays of heavy quarks provide access to fundamental parameters of the Standard Model, in particular the weak mixing angles of the Cabibbo-Kobayashi-Maskawa matrix. There is great hope that experiments with *B* mesons may lead to the first precise determination of the fourth CKM parameter, the complex phase. While the underlying decay of the heavy quark is governed by the weak interaction, it is the strong force that is responsible for the formation of the hadrons that are observed by experimenters. Although this complicates the extraction of the Standard Model parameters from the experimental data it also means that decays of *B* mesons provide an important laboratory to test our understanding of the strong interaction.

New results that were added to this edition fall into two categories. Arguably the most exciting development since the last edition of this review is the progress in *b*-quark decays beyond the tree level. Gluonic penguin decays such as $B \to K^-\pi^+$ have been measured for the first time providing us with new opportunities to search for physics beyond the Standard Model and/or to probe the phase structure of the CKM matrix.

At tree level, *i.e.* for $b \to c$ transitions, the CLEO collaboration used a sample of more than 6 million *B* decays to update branching fractions for many exclusive hadronic decay channels. New results on semileptonic decays have been reported by CLEO and the LEP collaborations. Lifetime measurements improved steadily and now have reached a precision of a few percent.

Heavy flavor physics is a very dynamic field and in this brief review it is impossible to do justice to all recent theoretical and experimental developments. I will highlight a few new results but otherwise refer the interested reader to several excellent reviews [1-4].

Production and spectroscopy: Elementary particles are characterized by their masses, lifetimes and internal quantum numbers. The bound states with a *b* quark and a $\overline{u}$ or $\overline{d}$ antiquark are referred to as the B_d ($\overline{B^0}$) and the B_u (B^-) mesons, respectively. The first excitation is called the B^* meson. B^{**} is the generic name for the four orbitally excited ($L = 1$) *B*-meson states that correspond to the *P*-wave mesons in the charm system, D^{**}. Mesons containing an *s* or a *c* quark are denoted B_s and B_c, respectively.

Experimental studies of *b* decay are performed at the $\Upsilon(4S)$ resonance near production threshold as well as at higher energies in proton-antiproton collisions and *Z* decays. Most new results from CLEO are based on a sample of $\approx 3.1 \times 10^6$ $B\overline{B}$ events. At the Tevatron, CDF and DØ have collected 100

pb^{-1} of data. Operating at the Z resonance each of the four LEP collaborations recorded slightly under a million $b\bar{b}$ events while the SLD experiment collected about 0.2 million hadronic Z decays.

For quantitative studies of B decays the initial composition of the data sample must be known. The $\Upsilon(4S)$ resonance decays only to $B^0\overline{B}^0$ and B^+B^- pairs, while at high-energy collider experiments heavier states such as B_s or B_c mesons and *b*-flavored baryons are produced as well. The current experimental limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level [5]. CLEO has measured the ratio of charged to neutral $\Upsilon(4S)$ decays using semileptonic B decays and found [6]

$$\frac{f_+}{f_0} = \frac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.13 \pm 0.14 \pm 0.13 \pm 0.06 \quad (1)$$

where the last error is due to the uncertainties in the ratio of B^0 and B^+ lifetimes. Assuming isospin symmetry an independent value can be obtained from $\mathcal{B}(B^- \to J/\psi K^{(*)-})$ and $\mathcal{B}(\overline{B}^0 \to J/\psi \bar{K}^{(*)0})$ [7]:

$$\frac{f_+}{f_0} = 1.11 \pm 0.17 \ . \quad (2)$$

This is consistent with equal production of B^+B^- and $B^0\overline{B}^0$ pairs and unless explicitly stated otherwise we will assume $f_+/f_0 = 1$. This assumption is further supported by the near equality of the B^+ and B^0 masses.

At high-energy collider experiments b quarks hadronize as $\bar{B}^0$, B^-, $\bar{B}^0_s$, and B^-_c mesons or as baryons containing b quarks. The *b*-hadron sample composition is not very precisely known although over the last few years significant improvements have been achieved, in particular thanks to B^0 oscillation measurements. The fractions f_{B^0}, f_{B^+}, f_{B_s}, and f_{Λ_b} of B^0, B^+, B^0_s, and b baryons in an unbiased sample of weakly decaying b hadrons produced at the Z resonance are shown in Table 1. They have been estimated by the LEP B oscillations working group [8] using the assumptions $f_{B^0} = f_{B^+}$ and $f_{B^0} + f_{B^+} + f_{B_s} + f_{\Lambda_b} = 1$ (the B_c^+ fraction is neglected). The procedure is summarized below.

An estimate of f_{B_s} is obtained from the measurements of the product branching fraction $f_{B_s} \times \mathcal{B}(B_s \to D_s^- \ell^+ \nu_\ell X)$. Under the assumption of equal semileptonic partial widths for *b*-flavored hadrons, results from the $\Upsilon(4S)$ experiments and the *b*-hadron lifetimes (Table 2) are combined to obtain an estimate for $\mathcal{B}(B_s \to D_s^- \ell \nu_\ell X)$. Together these are used to extract $f_{B_s} = (12.0^{+4.5}_{-3.4})\%$. A similar procedure is followed to obtain $f_{\Lambda_b} = (10.1^{+3.9}_{-3.1})\%$ from measurements of $f_{\Lambda_b} \times \mathcal{B}(\Lambda_b \to \Lambda_c^+ \ell^- \overline{\nu}_\ell X)$. A statistically independent estimate $f_{B_s} = (10.1^{+2.0}_{-1.9})\%$ is then derived from measurements of B^0 oscillations. This is done using measurements of the mixing parameters $\chi_d = (1/2) \cdot x_d^2/(1+x_d^2)$, in which $x_d = \Delta m_d \tau_{B^0}$, and $\overline{\chi} = f'_{B_s}\chi_s + f'_{B^0}\chi_d$. Here f'_{B_s} and f'_{B^0} are the fractions of B^0_s and B^0 mesons among semileptonic b decays. The dependence on the lifetimes is taken into account and $\chi_s = 1/2$ is assumed. This estimation is performed simultaneously with the Δm_d averaging described in the mixing section below. An average of the two estimates of f_{B_s}, taking the correlated systematic effects into account, yields $f_{B_s} = (10.5^{+1.8}_{-1.7})\%$ and hence the fractions of Table 1.

Table 1: Fractions of weakly decaying *b*-hadron species in $Z \to b\bar{b}$ decay.

b hadron	Fraction [%]
B^-	$39.7^{+1.8}_{-2.2}$
$\bar{B}^0$	$39.7^{+1.8}_{-2.2}$
$\bar{B}^0_s$	$10.5^{+1.8}_{-1.7}$
b baryons	$10.1^{+3.9}_{-3.1}$

To date, the existence of four *b*-flavored mesons (B^-, $\overline{B}^0$, B^*, B_s) as well as the Λ_b baryon has been established. Using exclusive hadronic decays such as $B^0_s \to J/\psi\phi$ and $\Lambda_b \to J/\psi\Lambda$ the masses of these states are now known with a precision of a few MeV. The current world averages of the B_s and the Λ_b mass are 5369.6 ± 2.4 MeV/c^2 and 5624 ± 9 MeV/c^2, respectively.

The B_c is the last weakly decaying bottom meson to be observed. Potential models predict its mass in the range 6.2 6.3 GeV/c^2. At the 1998 La Thuile conference CDF presented an analysis providing clear evidence for semileptonic $B_c \to J/\psi \ell X$ decays with $20.4^{+6.2}_{-5.5}$ observed events [13]. CDF reconstructs a B_c mass of $6.4 \pm 0.39 \pm\ 0.13$ MeV/c^2 and a B_c lifetime of $0.46^{+0.18}_{-0.16} \pm 0.03$ ps.

First indications of Σ_b and Ξ_b production have been presented by the LEP collaborations [14]. DELPHI has measured the $\Sigma_b^* - \Sigma_b$ hyperfine splitting to 56 ± 16 MeV [15].

Excited B-mesons states have been observed by CLEO, CUSB, and LEP. Evidence for B^{**} production has been presented by ALEPH, OPAL, and DELPHI [3]. Inclusively reconstructing a bottom hadron candidate combined with a charged pion from the primary vertex they see the B^{**} as broad resonance in the $M(B\pi)$ $M(B)$ mass distribution. The LEP experiments have also provided preliminary evidence for excited B_s^{**} states and DELPHI [16] has reported a possible observation of the B', the first radial excitation in the B meson system.

Lifetimes: In the naive spectator model the heavy quark can decay only via the external spectator mechanism and thus the lifetimes of all mesons and baryons containing b quarks would be equal. Nonspectator effects such as the interference between contributing amplitudes modify this simple picture and give rise to a lifetime hierarchy for *b*-flavored hadrons similar to the one in the charm sector. However, since the lifetime differences are expected to scale as $1/m_Q^2$, where m_Q is the mass of the heavy quark, the variation in the b system should be significantly smaller, of order 10% or less [17]. For the b system we expect

$$\tau(B^-) \geq \tau(\overline{B}^0) \approx \tau(B_s) > \tau(\Lambda_b^0) \ . \quad (3)$$

Measurements of lifetimes for the various *b*-flavored hadrons thus provide a means to determine the importance of nonspectator mechanisms in the b sector. Precise lifetimes are important for the determination of V_{cb}. They also enter in $B\overline{B}$ mixing measurements.

Over the past years the field has matured and advanced algorithms based on impact parameter or decay length measurements exploit the potential of silicon vertex detectors. However, in order to reach the precision necessary to test theoretical predictions, the results from different experiments need to be averaged. This is a challenging task that requires detailed knowledge of common systematic uncertainties and correlations between the results from different experiments. The average lifetimes for *b*-flavored hadrons given in this edition have been determined by the LEP B Lifetimes Working Group [19]. The papers used in this calculation are listed in the appropriate sections. A detailed description of the procedures and the treatment of correlated and uncorrelated errors can be found in [20]. The new world average *b*-hadron lifetimes are summarized in Table 2. Lifetime measurements have reached a precision that the average *b*-hadron lifetime result becomes sensitive to the composition of the data sample. The result listed in Table 2 takes into account correlations between different experiments and analysis techniques but does not correct for differences due to different admixtures of *b*-flavored hadrons. In order to estimate the size of this effect the available results have been divided into three sets. LEP measurements based on the identification of a lepton from the b decay yield $\tau_{b\ \text{hadron}} = 1.537 \pm 0.020\ \text{ps}^{-1}$ [21–23]. The average *b*-hadron lifetime based on inclusive secondary vertex techniques is $\tau_{b\ \text{hadron}} = 1.576 \pm 0.016\ \text{ps}^{-1}$ [24–29]. Finally, CDF [30] used ψ mesons to tag the b vertex resulting in $\tau_{b\ \text{hadron}} = 1.533 \pm 0.015^{+0.035}_{-0.031}\ \text{ps}^{-1}$.

Table 2: Summary of inclusive and exclusive *b*-hadron lifetime measurement.

Particle	Lifetime [ps]
B^0	1.56 ± 0.04
B^+	1.65 ± 0.04
B_s	1.54 ± 0.07
b baryon	1.22 ± 0.05
b hadron	1.564 ± 0.014

For comparison with theory lifetime ratios are preferred. Experimentally we find [19]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.04\pm0.04\,, \quad \frac{\tau_{B_s}}{\tau_{B^0}} = 0.99\pm0.05\,, \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.79\pm0.06 \tag{4}$$

while theory makes the following predictions [1]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1 + 0.05\left(\frac{f_B}{200\ \text{MeV}}\right)^2\,, \quad \frac{\tau_{B_s}}{\tau_{B^0}} = 1 \pm 0.01\,, \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.9\,. \tag{5}$$

In conclusion, the pattern of measured B-mesons lifetimes follows the theoretical expectations and non-spectator effects are observed to be small. However, the Λ_b-baryon lifetime is unexpectedly short. As has been noted by several authors, the observed value of the Λ_b lifetime is quite difficult to accommodate theoretically [31–33]. This apparent breakdown of the heavy-quark expansion for inclusive, non-leptonic B decays could be caused by violations of local quark-hadron duality. Neubert, however, argues that this conclusion is premature because a reliable field-theoretical calculation is still lacking. Exploring a reasonable parameter space for the unknown hadronic matrix elements he demonstrated that within the experimental errors theory can accommodate the measured lifetime ratios [1].

$B\overline{B}$ mixing: In production processes involving the strong or the electromagnetic interaction neutral B and $\overline{B}$ mesons can be produced. These flavor eigenstates are not eigenstates of the weak interaction which is responsible for the decay of neutral mesons containing b quarks. This feature and the small difference between the masses and/or lifetimes of the weak interaction eigenstates give rise to the phenomenon of B–$\overline{B}$ mixing. The formalism which describes B-meson mixing closely follows that used to describe K^0–$\overline{K}^0$ mixing, although the time scale characteristic of B^0–$\overline{B}^0$ oscillations is much shorter [34].

The ALEPH, DELPHI, L3, OPAL, SLD, and CDF experiments have performed explicit measurements of Prob($B^0 \to \overline{B}^0$) as a function of proper time to extract the oscillation parameter $\Delta m_d = x_d \Gamma_d$ [3]. The flavor of the final state b quark is tagged using the charge of a lepton, a fully or partially reconstructed charmed meson, or a charged kaon, from $b \to \ell^-$, $b \to c$ or $b \to c \to s$ decays respectively. For fully inclusive analyses, final state tagging techniques include jet charge and charge dipole methods. The initial state flavor is either tagged directly (same-side tag) or indirectly by tagging the flavor of the other b hadron produced in the event (opposite-side tag). Same-side tagging can be performed with a charged hadron produced in association with the B meson (possibly through a B^{**} state), and opposite-side tagging can be performed with a lepton or a kaon from the decay of the other b hadron. Jet charge techniques have also been used on both sides. If the B meson is produced with polarized beams, its polar angle with respect to the incoming beam axis can also be used to construct an initial state tag.

The LEP B oscillations working group has combined all published measurements of Δm_d to obtain an average of $0.470 \pm 0.019\ \text{ps}^{-1}$ [8]. The averaging procedure takes into account all correlated uncertainties as well as the latest knowledge on the *b*-hadron production fractions (Table 1), lifetimes (Table 2) and time-integrated parameters. Including the data from the time-integrated measurements performed by ARGUS and CLEO at the $\Upsilon(4S)$ resonance yields a combined result of $\Delta m_d = 0.464 \pm 0.018\ \text{ps}^{-1}$. Averaging time-dependent results from LEP and CDF and time-integrated measurements from CLEO and ARGUS the time-integrated mixing parameter χ_d is determined to 0.172 ± 0.010. As stated earlier, Δm_d and the *b*-hadron fractions are determined simultaneously, providing a self-consistent set of results.

The measurement of the oscillation parameter $\Delta m_s = x_s \Gamma_s$ for the B_s^0 meson combined with the results from the B^0–$\overline{B}^0$

oscillations allows the determination of the ratio of the CKM matrix elements $|V_{td}|^2/|V_{ts}|^2$ with significantly reduced theoretical uncertainties. For large values, as expected for the B_s^0 meson, time-integrated measurements of B_s^0 mixing become insensitive to Δm_s and one must make time-dependent measurements in order to extract this parameter. The observation of the rapid oscillation rate of the B_s^0 meson is an experimental challenge that is still to be met. The ALEPH, DELPHI, and OPAL experiments have provided lower limits on Δm_s [3]. The most sensitive analyses use inclusive leptons or fully reconstructed D_s^- mesons. All published data have been combined by the LEP B oscillations working group to yield the limit $\Delta m_s > 9.1$ ps^{-1} at 95% C.L. [8].

For the B_s meson, the quantity $\Delta\Gamma$ may be large enough to be observable [18]. Parton model calculations [9] and calculations with exclusive final states [10] suggest that the width difference may be 10–20%. This lifetime difference could be determined experimentally by using decays to final states with different CP. For example, a measurement of a difference in the lifetimes between $\overline{B}_s^0 \to J/\psi K_s$ and $\overline{B}_s^0 \to D_s^- \ell^+ \nu_\ell$ would yield $\Delta\Gamma/\Gamma^2$. It has also been suggested that such measurements could be used to constrain $|V_{ts}/V_{td}|^2$ if parton model calculations are reliable [11].

Semileptonic B decays: Measurements of semileptonic B decays are important to determine the weak couplings $|V_{cb}|$ and $|V_{ub}|$. In addition, these decays can be used to probe the dynamics of heavy quark decay. The leptonic current can be calculated exactly while corrections due to the strong interaction are restricted to the $b \to c$ and $b \to u$ vertices, respectively.

Experimentally, semileptonic decays have the advantage of large branching ratios and the characteristic signature of the energetic charged lepton. The neutrino, however, escapes undetected so a full reconstruction of the decaying B meson is impossible. Various techniques which take advantage of production at threshold or the hermiticity of the detector have been developed by the ARGUS, CLEO, and LEP experiments to overcome this difficulty.

Three different approaches have been used to measure the inclusive semileptonic rate $B \to X\ell\nu_\ell$. These are measurements of the inclusive single lepton momentum spectrum, measurements of dilepton events using charge and angular correlations, and measurements of the separate B^- and $\overline{B}^0$ branching ratios by using events which contain a lepton and a reconstructed B meson. The dilepton method has the least model-dependency and the current averages based on this method are listed in Table 3 [2]. Differences in $\mathcal{B}_{sl}$ measured at the $\Upsilon(4S)$ and the Z are expected due to the different admixture of b-flavored hadrons. Given the short Λ_b lifetime, however, the LEP value should be lower than the $\Upsilon(4S)$ result. While the experimental errors are still too large to draw any conclusions a potential systematic effect in the LEP results has been pointed out by Dunietz [12]. He noted that the LEP analyses have not yet been corrected for the recently observed production of $\overline{D}$ mesons in $\overline{B}$ decay.

A few new results on exclusive semileptonic B decays have been reported. The current world averages are listed in Table 3. It is interesting to compare the inclusive semileptonic branching fraction to the sum of branching fractions for exclusive modes. At the 2–3 σ level the exclusive modes saturate the inclusive rate leaving little room for extra contributions.

Table 3: Inclusive and exclusive semileptonic branching fractions of B mesons. $\mathcal{B}(\overline{B} \to X_u \ell^- \overline{\nu}_\ell) = 0.15 \pm 0.1\%$ has been included in the sum of the exclusive branching fractions.

Mode		Branching fraction [%]
$\overline{B} \to X\ell^-\overline{\nu}_\ell(\Upsilon(4S))$		10.18 ± 0.39
$b \to X\ell^-\overline{\nu}_\ell(Z)$		10.95 ± 0.32
$\overline{B} \to D\ell^-\overline{\nu}_\ell$		1.95 ± 0.27
$\overline{B} \to D^*\ell^-\overline{\nu}_\ell$		5.05 ± 0.25
$\overline{B} \to D^{(*)}\pi\ell^-\overline{\nu}_\ell$		2.3 ± 0.44
with $\overline{B} \to D_1^0(2420)\ell^-\overline{\nu}_\ell$	0.65 ± 0.11	
$\overline{B} \to D_2^{*0}(2460)\ell^-\overline{\nu}_\ell$	< 0.8 90% CL	
$\Sigma\mathcal{B}_{\text{exclusive}}$		9.45 ± 0.58

Dynamics of semileptonic B decay: Since leptons are not sensitive to the strong interaction, the amplitude for a semileptonic B decay can be factorized into two parts, a leptonic and a hadronic current. The leptonic factor can be calculated exactly while the hadronic part is parameterized by form factors. A simple example is the transition $B \to D\ell\nu_\ell$. The differential decay rate in this case is given by

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cb}^2|P_D^3 f_+^2(q^2) \tag{6}$$

where q^2 is the mass of the virtual W ($\ell\nu_\ell$) and $f_+(q^2)$ is the single vector form factor which gives the probability that the final state quarks will form a D meson. Since the leptons are very light the corresponding $f_-(q^2)$ form factor can be neglected. For $B \to D^*\ell\nu_\ell$ decays there are three form factors which correspond to the three possible partial waves of the $B \to D^*\widehat{W}$ system (here $\widehat{W}$ is the virtual W boson which becomes the lepton-antineutrino pair). Currently, form factors cannot be predicted by theory and need to be determined experimentally. Over the last years, however, it has been appreciated that there is a symmetry of QCD that is useful in understanding systems containing one heavy quark. This symmetry arises when the quark becomes sufficiently heavy to make its mass irrelevant to the nonperturbative dynamics of the light quarks. This allows the heavy quark degrees of freedom to be treated in isolation from the the light quark degrees of freedom. This is analogous to the canonical treatment of hydrogenic atoms, in which the spin and other properties of the nucleus can be neglected. The behavior and electronic structure of the atom are determined by the light electronic degrees of freedom. Heavy quark effective theory (HQET) was created by Isgur and Wise [35] who define a single universal form factor, $\xi(v \cdot v')$, known as the Isgur-Wise function. In this function v and v' are the four velocities of the initial and final state heavy mesons. The Isgur-Wise function cannot be calculated from first principles but unlike the hadronic form factors mentioned above it is universal. In the heavy quark limit it is the same for all heavy meson to heavy meson transitions and the four form factors parameterizing $B \to D^* \ell \nu_\ell$ and $B \to D \ell \nu_\ell$ decays can be related to this single function ξ.

In this framework the differential semileptonic decay rates as function of $w = v_B \cdot v_{D^{(*)}} = (m_B^2 + m_{D^{(*)}}^2 - q^2)/2m_B m_{D^{(*)}}$ are given by [1]

$$\begin{aligned}\frac{d\Gamma(\overline{B} \to D^* \ell \overline{\nu}_\ell)}{dw} =& \frac{G_F^2 M_B^5}{48\pi^3} r_*^3 (1-r_*)^2 \sqrt{w^2-1}(w+1)^2 \\ & \times \left[1 + \frac{4w}{w+1} \frac{1-2wr_* + r_*^2}{(1-r_*)^2}\right] |V_{cb}|^2 \mathcal{F}^2(w) \\ \frac{d\Gamma(\overline{B} \to D \ell \overline{\nu}_\ell)}{dw} =& \frac{G_F^2 M_B^5}{48\pi^3} r^3 (1+r)^2 (w^2-1)^{3/2} |V_{cb}|^2 \mathcal{G}^2(w) \quad (7)\end{aligned}$$

where $r_{(*)} = M_{D^{(*)}}/M_B$ and q^2 is the invariant momentum transfer. For $m_Q \to \infty$, the two form factors $\mathcal{F}(w)$ and $\mathcal{G}(w)$ coincide with the Isgur-Wise function $\xi(w)$.

Both CLEO [36] and ALEPH [37] have measured the differential decay rate distributions and extracted the ratio $\mathcal{G}(w)/\mathcal{F}(w)$ which is expected to be close to unity. As can be seen from the ALEPH result shown in Fig. 1, the data are compatible with a universal form factor $\xi(w)$

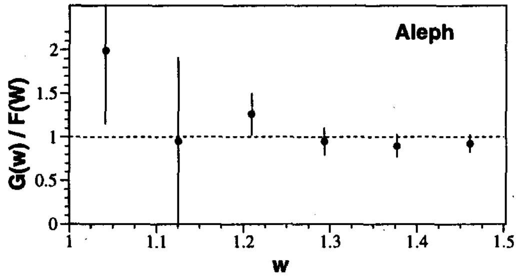


Figure 1: Ratio of the two form factors $\mathcal{G}(w)$ and $\mathcal{F}(w)$ in semileptonic B decay [37].

CLEO has also performed a direct measurement of the three form factors that are used to parameterize $B \to D^* \ell \nu_\ell$ decays [38]. These are usually expressed in terms of form factor ratios R_1 and R_2 [39]. At zero recoil, *i.e.* $w = 1$, CLEO finds $R_1 = 1.24 \pm 0.26 \pm 0.12$ and $R_2 = 0.72 \pm 0.18 \pm 0.07$. While the errors are still large, this is in good agreement with a theoretical prediction of $R_1 = 1.3 \pm 0.1$ and $R_2 = 0.8 \pm 0.2$ [1].

Extraction of $|V_{cb}|$***:*** The universal form factor $\xi(w)$ describes the overlap of wavefunctions of the light degrees of freedom in the initial and final heavy meson. At zero recoil, *i.e.* when the two mesons move with the same velocity, the overlap is perfect and the form factor is absolutely normalized, $\xi(1) = 1$. In principle, all that experimentalists have to do to extract a model-independent value for $|V_{cb}|$ is to measure $d\Gamma(B \to D^{(*)} \ell \nu_\ell)/dw$ for $w \to 1$. However, in the real world the b and c quarks are not infinitely heavy so corrections to the limiting case have to be calculated. After much theoretical effort, the current results are [1]:

$$\begin{aligned}\mathcal{F}(1) =& 0.924 \pm 0.027 \, , \\ \mathcal{G}(1) =& 1.00 \pm 0.07 \, . \end{aligned} \qquad (8)$$

Furthermore, the shape of the form factor has to be parameterized because at zero recoil the differential decay rate actually vanishes. Experimentally, the decay rate is measured as function of w and then extrapolated to zero recoil using an expansion of form

$$\mathcal{F}(w) = \mathcal{F}(1)\left(1 - \widehat{\rho}^2(w-1)\right) \; . \qquad (9)$$

The slope $\widehat{\rho}^2$ of the form factor and $|V_{cb}|$ are correlated. The current world averages for $|V_{cb}|$ and $\widehat{\rho}$ as extracted from exclusive semileptonic B decays have been compiled by Drell [2]. This value of $|V_{cb}|$ is in good agreement with independent determinations of $|V_{cb}|$ from inclusive B decays.

Table 4: Current world averages.

Mode	$\lvert V_{cb} \rvert$	$\widehat{\rho}^2$
$\overline{B} \to D^* \ell^- \overline{\nu}_\ell$	0.0387 ± 0.0031	0.71 ± 0.11
$\overline{B} \to D \ell^- \overline{\nu}_\ell$	0.0394 ± 0.0050	0.66 ± 0.19

Hadronic B decays: In hadronic decays of B mesons the underlying weak transition of the b quark is overshadowed by strong interaction effects caused by the surrounding cloud of light quarks and gluons. While this complicates the extraction of CKM matrix elements from experimental results it also turns the B meson into an ideal laboratory to study our understanding of perturbative and non-perturbative QCD, of hadronization, and of Final State Interaction (FSI) effects.

The precision of the experimental data has steadily improved over the past years. In 1997 CLEO updated most branching fractions for exclusive $B \to (n\pi)^- D^{(*)}$ and $B \to J/\psi K^{(*)}$ transitions. New, tighter limits on color suppressed decays such as $\overline{B} \to D^0 \pi^0$ have been presented [41] and a new measurement of the polarization in $B \to J/\psi K^*$ resolved an outstanding discrepancy between theory and experiment [40]. Progress has been made in experimental techniques. Last summer CLEO presented several analyses based on partial reconstruction [48,49]. In this method, D^* mesons are not fully reconstructed but rather tagged by the presence of the characteristic slow pion from the $D^* \to D^0 \pi$ decay. This results in substantially increased event yields, *e.g.*, 281 ± 56 $D^{**}(2420)$ candidates have been reconstructed. The preliminary results are

$$\begin{aligned}\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-) =& (2.81 \pm 0.11 \pm 0.21 \pm 0.05) \times 10^{-3} \\ \mathcal{B}(B^- \to D^{*0}\pi^-) =& (4.81 \pm 0.42 \pm 0.40 \pm 0.21) \times 10^{-3} \\ \mathcal{B}(B^- \to D_1(2420)\pi^-) =& (1.17 \pm 0.24 \pm 0.16 \pm 0.03) \times 10^{-3} \\ \mathcal{B}(B^- \to D_2^*(2460)\pi^-) =& (2.1 \pm 0.8 \pm 0.3 \pm 0.05) \times 10^{-3} . \, (10)\end{aligned}$$

The second systematic error reflects the uncertainty in the D^* branching fractions.

Gronau and Wyler [50] first suggested that decays of the type $B \to DK$ can be used to extract the angle γ of the CKM unitarity triangle, $\gamma \approx \arg(V_{ub})$. The first example of such a Cabibbo suppressed mode has recently been observed by CLEO [51]:

$$\frac{\mathcal{B}(B^- \to D^0 K^-)}{\mathcal{B}(B^- \to D^0\pi^-)} = 0.055 \pm 0.014 \pm 0.005 \ . \tag{11}$$

Measurements of exclusive hadronic B decays have reached sufficient precision to challenge our understanding of the dynamics of these decays. It has been suggested that in analogy to semileptonic decays, two-body hadronic decays of B mesons can be expressed as the product of two independent hadronic currents, one describing the formation of a charm meson and the other the hadronization of the remaining $\overline{u}d$ (or $\overline{c}s$) system from the virtual W^-. Qualitatively, for a B decay with a large energy release, the $\overline{u}d$ pair, which is produced as a color singlet, travels fast enough to leave the interaction region without influencing the second hadron formed from the c quark and the spectator antiquark. The assumption that the amplitude can be expressed as the product of two hadronic currents is called "factorization" in this paper. By comparing exclusive hadronic B decays to the corresponding semileptonic modes the factorization hypothesis has been experimentally confirmed for decays with large energy release [40]. Note that it is possible that factorization will be a poorer approximation for decays with smaller energy release or larger q^2. For internal spectator decays the validity of the factorization hypothesis is also questionable and requires experimental verification. The naive color transparency argument used in the previous sections is not applicable to decays such as $B \to J/\psi K$, and there is no corresponding semileptonic decay to compare to. For internal spectator decays one can only compare experimental observables to quantities predicted by models based on factorization. Two such quantities are the production ratio

$$\mathcal{R} = \frac{\mathcal{B}(B \to J/\psi K^*)}{\mathcal{B}(B \to J/\psi K)} \tag{12}$$

and the amount of longitudinal polarization Γ_L/Γ in $B \to J/\psi K^*$ decays. Previous experimental results, $\mathcal{R} = 1.68 \pm 0.33$ and $\Gamma_L/\Gamma = 0.78 \pm 0.04$, were inconsistent with all model predictions. The theory had difficulties in simultaneously accommodating a large longitudinal polarization and a large vector-to-pseudoscalar production ratio. Non-factorizable contributions that reduce the transverse amplitude were proposed to remedy the situation. New experimental results, however, make this apparent breakdown of the factorization hypothesis less likely. The CLEO collaboration published new data on $B \to$ charmonium transitions [7]. Their values,

$$\mathcal{R} = 1.45 \pm 0.20 \pm 0.17 \ , \ \Gamma_L/\Gamma = 0.52 \pm 0.07 \pm 0.04 \ , \tag{13}$$

are now consistent with factorization-based models.

In the decays of charm mesons, the effect of color suppression is obscured by the effects of FSI or reduced by nonfactorizable effects. Because of the larger mass of the b quark, a more consistent pattern of color-suppression is expected in the B system, and current experimental results seem to support that color-suppression is operative in hadronic decays of B mesons. Besides $B \to$ charmonium transitions no other color-suppressed decay has been observed experimentally [41]. The current upper limit on $\mathcal{B}(\overline{B}^0 \to D^0\pi^0)$ is 0.012% at 90% C.L.

By comparing hadronic B^- and $\overline{B}^0$ decays, the relative contributions from external and internal spectator decays have been disentangled. For all decay modes studied the B^- branching ratio was found to be larger than the corresponding $\overline{B}^0$ branching ratio indicating constructive interference between the external and internal spectator amplitudes. In the BSW model [42] the two amplitudes are proportional to effective coefficients, a_1 and a_2, respectively. A least squares fit using the latest branching ratio measurements and a model by Neubert *et al.* [43] gives

$$a_2/a_1 = 0.22 \pm 0.04 \pm 0.06 \ , \tag{14}$$

where we have ignored uncertainties in the theoretical predictions. The second error is due to the uncertainty in the B-meson production fractions (f_+, f_0) and lifetimes (τ_+, τ_0) that enter into the determination of a_1/a_2 in the combination $(f_+\tau_+/f_0\tau_0)$. As this ratio increases, the value of a_2/a_1 decreases. Varying $(f_+\tau_+/f_0\tau_0)$ in the allowed experimental range (±20%) excludes a negative value of a_2/a_1. Other uncertainties in the magnitude of the decay constants f_D and f_{D^*} as well as in the hadronic form factors can change the magnitude of a_2/a_1 but not its sign.

The magnitude of a_2 determined from this fit to the ratio of B^- and $\overline{B}^0$ branching fractions is consistent with the value of $|a_2|$ determined from the fit to the $B \to J/\psi$ decay modes which only via the color suppressed amplitude. The coefficient a_1 also shows little or no process dependency.

The observation that the coefficients a_1 and a_2 have the same relative sign in B^- decay came as a surprise, since destructive interference was observed in hadronic charm decay. The sign of a_2 disagrees with the theoretical extrapolation from the fit to charm meson decays using the BSW model. It also disagrees with the expectation from the $1/N_c$ rule [44]. The result may be consistent with the expectation of perturbative QCD [45]. B. Stech proposed that the observed interference pattern in charged B and D decay can be understood in terms of the running strong coupling constant α_s [46]. A solution based on PQCD factorization theorems has been suggested by B. Tseng and H.N. Li [47].

Although constructive interference has been observed in all the B^- modes studied so far, these comprise only a small fraction of the total hadronic rate. It is conceivable that higher multiplicity B^- decays demonstrate a very different behaviour.

It is intriguing that $|a_1|$ determined from $B \to D^{(*)}\pi$, $D^{(*)}\rho$ modes agrees well with the value of a_1 extracted from $B \to DD_s$ decays. The observation of color-suppressed decays such as

$\overline{B}^0 \to D^0\pi^0$ would give another measure of $|a_2|$ complementary to that obtained from $B \to$ charmonium decays.

In summary, experimental results on exclusive B decay match very nicely with theoretical expectations. Unlike charm the b quark appears to be heavy enough so that corrections due to the strong interaction are small. Factorization and color-suppression are at work. An intriguing pattern of constructive interference in charged B decays has been observed.

Inclusive hadronic decays: Over the last years inclusive B decays have become an area of intensive studies, experimentally as well as theoretically. Since the hadronization process to specific final state mesons is not involved in inclusive calculations the theoretical results and predictions are generally believed to be more reliable.

CLEO and the LEP collaborations presented new measurements of inclusive $b \to c$ transitions that can be used to extract n_c, the number of charm quarks produced per b decay. Naively we expect $n_c = 115\%$ with the additional 15% coming from the decay of the W boson to $\bar{c}s$. This expectation can be verified experimentally by adding all inclusive $b \to c$ branching fractions. Using CLEO and LEP results we can perform the calculation shown in Table 5. Modes with 2 charm quarks in the final state are counted twice. For the unobserved $B \to \eta_c X$ decay we take the experimental upper limit. B_s mesons and b baryons produced at the Z but not at the $\Upsilon(4S)$ cause the increase in D_s and Λ_c production rates seen by LEP. To first order, however, this should not affect the charm yield and it should be compensated by reduced branching fractions for D mesons. This is not reflected in the current data but the errors are still large. In addition, there are significant uncertainties in the D_s and Λ_c absolute branching fractions.

Table 5: Charm yield per B decay.

Channel	Branching fraction [%]	
	$\Upsilon(4S)$ [40]	LEP [2]
$B \to D^0X$	63.6 ± 3.0	57.6 ± 2.6
$+\ B \to D^+X$	23.5 ± 2.7	22.4 ± 1.9
$+\ B \to D_s^+X$	12.1 ± 1.7	19.1 ± 5.0
$+\ B \to \Lambda_c^+X$	2.9 ± 2.0	11.4 ± 2.0
$+\ B \to \Xi_c^{+,0}X$	2.0 ± 1.0	6.3 ± 2.1
$+\ 2\times\ B \to J/\psi_{\rm direct}X$	0.8 ± 0.08	
$+\ 2\times\ B \to \psi(2S)_{\rm direct}X$	0.35 ± 0.05	
$+\ 2\times\ B \to \chi_{c1}X$	0.37 ± 0.07	
$+\ 2\times\ B \to \chi_{c2}X$	0.25 ± 0.1	
$+\ 2\times\ B \to \eta_cX$	< 0.9 (90%C.L.)	
$+\ 2\times\ b \to (c\bar{c})X$		3.4 ± 1.2
n_c	110 ± 5	120 ± 7

Inclusive $b \to c\bar{c}s$ transitions: It was previously assumed that the conventional $b \to c\bar{u}d \to DX$ and $b \to c\bar{c}s \to D\overline{D}_sX$ mechanisms account for all D meson production in B decay. Buchalla *et al.* [57] suggested that a significant fraction of D mesons could also arise from $b \to c\bar{c}s$ transitions with light quark pair production at the upper vertex, *i.e.* $b \to c\bar{c}s \to D\overline{D}X_s$. The two mechanisms can be distinguished by the different final states they produce. In the first case the final state includes only D mesons whereas in the second case two D mesons can be produced, one of which has to be a $\overline{D}$.

Table 6: CLEO results on $B \to DDK$ decays (preliminary).

Mode	Branching fraction [%]
$\mathcal{B}(\overline{B}^0 \to D^{*+}\overline{D}^0K^-)$	$0.45^{+0.25}_{-0.19} \pm 0.08\%$
$\mathcal{B}(B^- \to D^{*0}\overline{D}^0K^-)$	$0.54^{+0.33}_{-0.24} \pm 0.12\%$
$\mathcal{B}(\overline{B}^0 \to D^{*+}\overline{D}^{*0}K^-)$	$1.30^{+0.61}_{-0.47} \pm 0.27\%$
$\mathcal{B}(B^- \to D^{*0}\overline{D}^{*0}K^-)$	$1.45^{+0.78}_{-0.58} \pm 0.36\%$

Two routes to search for this addition to $\Gamma(b \to c\bar{c}s)$ have been pursued experimentally. In an exclusive search for $B \to D\overline{D}K$ decays CLEO required the final state to include a D and a $\overline{D}$ meson. Statistically significant signals are observed for several $D^{(*)}\overline{D}^{(*)}$ combinations. The preliminary CLEO results are listed in Table 6 [52]. While the observation of these decays proves the existence of $\overline{D}$-meson production at the upper vertex, a more inclusive measurement is needed to estimate the overall magnitude of this effect. A recent CLEO analysis exploits the fact that the flavor of the final state D-meson tags the decay mechanism. A high momentum lepton ($p_\ell > 1.4$ GeV/c) from the second B meson is used to classify the flavor of the decaying B meson. $b \to c\bar{u}d$ transitions lead to $D\ell^+$ combinations while the observation of $\overline{D}\ell^+$ identifies the new $b \to c\bar{c}s$ mechanism. Angular correlations are used to remove combinations with both particles coming from the same B meson. CLEO finds [53]

$$\frac{\Gamma(\overline{B} \to \overline{D}X)}{\Gamma(\overline{B} \to DX)} = 0.100 \pm 0.026 \pm 0.016\,, \qquad (15)$$

which implies

$$\mathcal{B}(\overline{B} \to \overline{D}X) = 0.079 \pm 0.022\,. \qquad (16)$$

$b \to D\overline{D}X$ decays have also been observed at LEP. ALEPH [54] finds

$$\mathcal{B}(B \to D^0\overline{D}^0X + D^0D^{\mp}X) = 0.078^{+0.02}_{-0.018}{}^{+0.017}_{-0.015}{}^{+0.005}_{-0.004}\,, \qquad (17)$$

where the last error reflects the uncertainty in D meson branching fractions. DELPHI reports the observation of $D^{*+}D^{*-}$ production [55]

$$\mathcal{B}(\overline{B} \to D^{*+}D^{*-}X) = 0.01 \pm 0.002 \pm 0.003\,. \qquad (18)$$

These results are still preliminary. We can now calculate $n_{cc} = \mathcal{B}(b \to c\bar{c}s)$. Using the data listed in Table 5 and the new result, $\mathcal{B}(\overline{B} \to \overline{D}X) = 0.079 \pm 0.022$, we find

$$n_{cc} = 23.9 \pm 3.0\%\,. \qquad (19)$$

The contribution from $B \to \Xi_c^0X$ was reduced by 1/3 to take into account the fraction that is not produced by the $b \to c\bar{c}s$ subprocess but by $b \to c\bar{u}d$ + $s\bar{s}$ quark pair production.

This result is consistent with theoretical predictions, $\mathcal{B}(b \to c\bar{c}s) = 22 \pm 6\%$ [31,56]. n_{cc} is related to n_c, the number of charm quarks produced per b decay. We expect $n_c = 1 + n_{cc} - n_{B\to \text{no charm}}$ which is consistent with the LEP result reported above. If the smaller value of n_c observed by CLEO is confirmed it could indicate a problem with $\Gamma(b \to c\bar{u}d)$ or a very large $\mathcal{B}(b \to sg)$.

Charm counting and the semileptonic branching fraction: The charm yield per B-meson decay is related to an intriguing puzzle in B physics: the experimental value for the semileptonic branching ratio of B mesons, $\mathcal{B}(B \to X\ell\nu_\ell) = 10.18 \pm 0.39\%$ ($\Upsilon(4S)$), is significantly below the theoretical lower bound $\mathcal{B} > 12.5\%$ from QCD calculations within the parton model [58]. Since the semileptonic and hadronic widths are connected via

$$1/\tau = \Gamma = \Gamma_{\text{semileptonic}} + \Gamma_{\text{hadronic}} \tag{20}$$

an enhanced hadronic rate is necessary to accommodate the low semileptonic branching fraction. The hadronic width can be expressed as

$$\Gamma_{\text{hadronic}} = \Gamma(b \to c\bar{c}s) + \Gamma(b \to c\bar{u}d) + \Gamma(b \to sg + \text{no charm})\,. \tag{21}$$

Several explanations of this $n_c/\mathcal{B}_{\text{sl}}$ discrepancy have been proposed:

1. Enhancement of $b \to c\bar{c}s$ due to large QCD corrections or a breakdown of local duality;
2. Enhancement of $b \to c\bar{u}d$ due to non-perturbative effects;
3. Enhancement of $b \to sg$ and/or $b \to dg$ due to new physics;
4. Systematic problem in the experimental results;

or the problem could be caused by some combination of the above. Arguably the most intriguing solution to this puzzle would be an enhanced $b \to sg$ rate but as we will see in the next section, new results from CLEO and LEP show no indication for new physics and place tight limits on this process.

$\mathcal{B}(b \to c\bar{u}d)$ has been calculated to next-to-leading order. Bagan *et al.* [59] find:

$$r_{ud} = \frac{\mathcal{B}(b \to c\bar{u}d)}{\mathcal{B}(b \to c\ell\nu_\ell)} = 4.0 \pm 0.4 \to \mathcal{B}(b \to c\bar{u}d)_{\text{theory}} = 41 \pm 4\%\,. \tag{22}$$

Experimentally, we can extract this quantity in the way shown in Table 7.

Table 7: Experimental extraction of $\mathcal{B}(b \to c\bar{u}d)$.

$\mathcal{B}(b \to c\bar{u}d)_{\text{exp.}} =$	$\mathcal{B}(B \to (D+\overline{D})X)$	$87.1 \pm 4.0\%$
	$+\ \mathcal{B}(B \to D_sX)_{\text{lower vertex}}$	$1.8 \pm 0.9\%$
	$+\ \mathcal{B}(B \to \text{baryons}X)$	$4.6 \pm 2.1\%$
	$-\ 2 \times \mathcal{B}(B \to \overline{D}X)_{\text{upper vertex}}$	$2 \times (7.9 \pm 2.2\%)$
	$-\ \mathcal{B}(B \to D_sX)$	$12.1 \pm 1.7\%$
	$-\ 2.25 \times \mathcal{B}(b \to c\ell\nu_\ell)$	$22.9 \pm 0.9\%$
		$43 \pm 6\%$

Here upper vertex refers to the W decay while lower vertex refers to the $b \to c$ transition. For the total semileptonic branching fraction we assumed $\mathcal{B}(b \to c\tau\nu_\tau) = 0.25 \times \mathcal{B}(b \to ce\nu_e)$. There is good agreement between theory and experiment but the errors are still too large to completely rule out an enhanced $b \to c\bar{u}d$ rate.

The theoretically preferred solution calls for an enhancement of the $b \to c\bar{c}s$ channel [31,59]. Increasing the $b \to c\bar{c}s$ component, however, would increase the average number of c quarks produced per b-quark decay as well as n_{cc}, the number of b decays with 2 charm quarks in the final state. Figure 2 taken from Ref. 1 shows the theoretical range together with experimental values from LEP and CLEO/ARGUS.

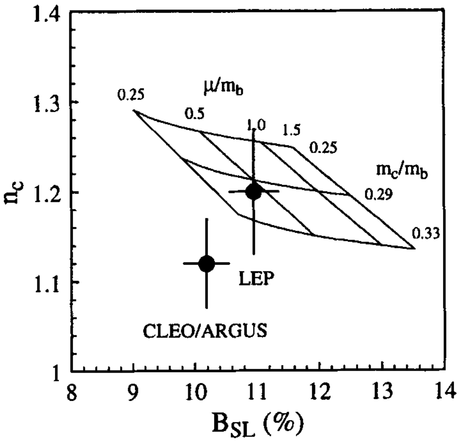


Figure 2: Charm yield (n_c) versus semileptonic branching fraction.

While the experimental value of n_{cc} is consistent with this scenario, the value of n_c measured at the $\Upsilon(4S)$ appears to be too low at the few σ-level. Systematic problems with D meson branching fractions have been pointed out as a potential solution [12] but new results from ALEPH [60] and CLEO [61] on $\mathcal{B}(D^0 \to K^-\pi^+)$ make this less likely.

After years of experimental and theoretical efforts the missing charm/$\mathcal{B}_{sl}$ problem has begun to fade away. There is still a discrepancy between the charm yield measured by CLEO and the theoretical prediction. More data are needed to either resolve this issue or to demonstrate that the problem persists.

Rare B decays: All B-meson decays that do not occur through the usual $b \to c$ transition are known as rare B decays. These include semileptonic and hadronic $b \to u$ decays that—although at tree level—are suppressed by the small CKM matrix element V_{ub} as well as higher order processes such as electromagnetic and gluonic penguin decays. Branching fractions are typically around 10^{-5} for exclusive channels and sophisticated background suppression techniques are essential for these analyses.

Arguably the most exciting new experimental results since the last edition of this review are in the field of rare B decays. For many charmless B-decay modes the addition of new data and the refinement of analysis techniques allowed CLEO to observe signals where previously there have been upper limits. For other channels new tighter upper limits have been published [62].

Semileptonic $b \to u$ transitions: The simplest diagram for a rare B decay is obtained by replacing the $b \to c$ spectator diagram a CKM suppressed $b \to u$ transition. These decays probe the small CKM matrix element V_{ub}, the magnitude of which sets bounds on the combination $\rho^2 + \eta^2$ in the Wolfenstein parameterization of the CKM matrix. Measurements of the magnitude of V_{ub} have been obtained from both inclusive and exclusive semileptonic B decays [63,65]. Inclusive analyses at the $\Upsilon(4S)$ focus on leptons in the endpoint region of the single lepton spectrum which are kinematically incompatible with coming from a $b \to c$ transition. Models are used to extrapolate to the full spectrum from which $|V_{ub}| = (3.7 \pm 0.6) \times 10^{-3}$ is extracted [64]. The error is dominated by uncertainties in the models.

Exclusive semileptonic $b \to u$ transitions have been observed by the CLEO Collaboration [63]. Using their large data sample and employing the excellent hermiticity of the CLEO II detector they were able to measure $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$ and $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}$ which can be used to extract $|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}$. The last error in these results reflects the model-dependence.

While the consistency of the two methods is encouraging, the errors, in particular the theoretical uncertainties, are still large.

Hadronic $b \to u$ transitions: Exclusive hadronic $b \to u$ transitions still await experimental discovery. Using 3.3×10^6 $B\overline{B}$ decays CLEO searched for exclusive charmless final states such as $\pi^+\pi^-$ and $\rho^+\pi^-$. No significant excess has been observed and some of the new upper limits are listed in Table 8 [66]. The mode $B^0 \to \pi^+\pi^-$ is of particular interest for CP-violation studies in the B-meson system. The branching fraction is smaller than initial expectations and extracting $\sin(2\alpha)$, *i.e.* one of the angles in the unitarity triangle, will become increasingly more difficult. Assuming factorization we can use CLEO's measurement of $B^0 \to \pi^- \ell^+ \nu_\ell$ and the ISGW II form factors [67] to predict $\mathcal{B}(B^0 \to \pi^+\pi^-) = (1.2 \pm 0.4) \times 10^{-5}$ and $\mathcal{B}(B^+ \to \pi^+\pi^0) = (0.6 \pm 0.2) \times 10^{-5}$.

Electromagnetic penguin decays: The observation of the decay $B \to K^*(892)\gamma$, reported in 1993 by the CLEO II experiment, provided first evidence for the one-loop penguin diagram [69]. Using a larger data sample the analysis was re-done in 1996 yielding [69]

$$\mathcal{B}(B \to K^*\gamma) = (4.2 \pm 0.8 \pm 0.6) \times 10^{-5} \; . \qquad (23)$$

Table 8: Summary of new CLEO results on $B \to \pi\pi, K\pi$ and KK branching fractions. The branching fractions and the 90% C.L. upper limits are given in units of 10^{-5}. Using the notation of Gronau *et al.* [68] the last column indicates the dominant amplitudes for each decay (T, C, P, E denote tree, color suppressed, penguin, and exchange amplitudes and the unprimed (primed) amplitudes refer to $\overline{b} \to \overline{u}u\overline{d}$ ($\overline{b} \to \overline{u}u\overline{s}$) transitions, respectively.)

Mode ($B \to$)	$\mathcal{B}$	Amplitude	Theoretical expectation
$\pi^+\pi^-$	< 1.5	$-(T+P)$	0.8–2.6
$\pi^+\pi^0$	< 2.0	$-(T+C)/\sqrt{(2)}$	0.4–2.0
$\pi^0\pi^0$	< 0.93	$-(C-P)/\sqrt{(2)}$	0.006–0.1
$K^+\pi^-$	$1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.1$	$-(T'+P')$	0.7–2.4
$K^+\pi^0$	< 1.6	$-(T'+C'+P')/\sqrt{(2)}$	0.3–1.3
$K^0\pi^-$	$2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2$	P'	0.8–1.5
$K^0\pi^0$	< 4.1	$-(C'-P')/\sqrt{(2)}$	0.3–0.8
K^+K^-	< 0.43	E	—
K^+K^0	< 2.1	P	0.07–0.13
K^0K^0	< 1.7	P	0.07–0.12
$(K^+ \text{ or } \pi^+)\pi^0$	$1.6^{+0.6}_{-0.5} \pm 0.3 \pm 0.2$	—	—

The observed branching fractions were used to constrain a large class of Standard Model extensions [72]. However, due to the uncertainties in the hadronization, only the inclusive $b \to s\gamma$ rate can be reliably compared with theoretical calculations. This rate can be measured from the endpoint of the inclusive photon spectrum in B decay. CLEO [70] found

$$\mathcal{B}(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4} \, (\text{CLEO}) \; . \qquad (24)$$

ALEPH used a lifetime tagged sample of $Z \to b\overline{b}$ events to search for high-energy photons in the hemisphere opposite to the tag. This allows them to measure the photon spectrum from B decays which ultimately leads to [71]

$$\mathcal{B}(b \to s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4} \, (\text{ALEPH}) \; . \qquad (25)$$

Our theoretical understanding of inclusive $b \to s\gamma$ transitions has been significantly enhanced by two new calculations that now include all terms to next-to-leading order [73]. The expected Standard Model rate, while slightly larger now, is still consistent with both the CLEO and ALEPH results. The substantially reduced uncertainties result in tighter constraints on new physics such as double Higgs models [2].

Gluonic penguin decays: A larger total rate is expected for gluonic penguins, the counterpart of $b \to s\gamma$ with the photon replaced by a gluon.

Experimentally, it is a major challenge to measure the inclusive $b \to sg$ rate. The virtual gluon hadronizes as a $q\overline{q}$ pair without leaving a characteristic signature in the detector. CLEO extended $D - \ell$ correlation measurements described in the section on hadronic B decays to obtain the flavor specific decay rate $\Gamma(\overline{B} \to DX)_{\text{lower vertex}}/\Gamma_{\text{total}}$. This quantity should be 1 minus corrections for charmonium production, $b \to u$ transitions, $B \to$ baryons, and D_s production at the lower vertex. Most importantly, the $b \to sg$ rate must also be subtracted. To remove uncertainties due to $\mathcal{B}(D^0 \to K^-\pi^+)$

CLEO normalizes to $\Gamma(\overline{B} \to DX\ell\nu_\ell)/\Gamma(\overline{B} \to X\ell\nu_\ell)$. Their preliminary result is

$$\frac{\Gamma(\overline{B} \to DX)_{\text{lower vertex}}/\Gamma_{\text{total}}}{\Gamma(\overline{B} \to DX\ell\nu_\ell)/\Gamma(\overline{B} \to X\ell\nu_\ell)} = 0.901 \pm 0.034 \pm 0.014 \quad (26)$$

whereas $0.903 \pm 0.018 - \mathcal{B}(b \to sg)$ was expected. This corresponds to an upper limit of $\mathcal{B}(b \to sg) < 6.8\%$ [53]. DELPHI [55] studied the the p_T spectrum of charged kaons in B decays and found a model-dependent limit $\mathcal{B}(b \to sg) < 5\%$ (95% C.L.). These results agree well with the Standard Model prediction of $\mathcal{B}(\overline{B} \to \text{no charm}) = (1.6 \pm 0.8)\%$ [74] and there is little experimental support for new physics and an enhanced $b \to sg$ rate [75]. However, experimental uncertainties are still large and it is too early to draw final conclusions. Last summer, the SLD collaboration reported an excess in the kaon spectrum at high p_T [76].

Exclusive decays such as $B^0 \to K^+\pi^-$ are strongly suppressed to first order and are expected to proceed via loop processes. CLEO studied these decay modes and last summer reported the first observation of $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$ decays. The results are listed in Table 8. $\mathcal{B}(B^+ \to K^0\pi^+)$ is of particular interest since it directly measures the strength of the gluonic penguin amplitude (Table 8). The smaller rate measured for $B^0 \to K^+\pi^-$ could indicate that the two amplitudes contributing to this channel interfere destructively. This observation has been extended by Fleischer and Mannel [77] to place some constraints on γ, the phase of V_{ub}.

CLEO extended their search of charmless B decay to modes including light meson resonances such as ρ, K^*, ω, η, and η' [78]. Statistically significant signals have been seen in several channels; the results are summarized in Table 9.

Table 9: Summary of new CLEO results on rare B decays involving light meson resonances.

Mode	Branching fraction ($\times 10^{-5}$)
$B \to \omega K^+$	$1.5^{+0.7}_{-0.6} \pm 0.3$
$B \to \eta' K^+$	$7.1^{+2.5}_{-2.1} \pm 0.9$
$B \to \eta' K^0$	$5.3^{+2.8}_{-2.2} \pm 1.2$
$B \to \eta' X_s$	$62 \pm 16 \pm 13$ $(2.0 < p_{\eta'} < 2.7\,\text{GeV/c})$

A surprisingly large signal has been observed for $B \to \eta' K$ (see Fig. 3) while no evidence for ηK or $\eta' K^*$ final states has been found [79].

The interpretation of these results is subject of an ongoing discussion. It has been suggested that interference between different penguin amplitudes causes $\mathcal{B}(B \to \eta' K)$ to be larger than $\mathcal{B}(B \to \eta K)$ [80,81]. Other proposals try to explain the large $\eta' K$ rate by the anomalous coupling of the η' to glue [82,83], a $c\bar{c}$ component in the η' [84] or by an enhanced $b \to sg$ rate due to some new physics [85]. Additional experimental input to this puzzle comes from a CLEO measurement of inclusive η' production. At high momenta the η' spectrum is dominated by $B \to \eta' X_s$ decays and a study of the system recoiling against the η' shows that large masses $m(X_s)$ are preferred [86].

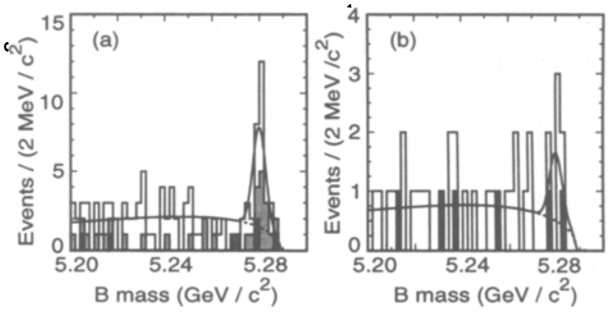


Figure 3: Beam-constrained mass for (a) $B^+ \to \eta' h^+$ with $h^+ = K^+$ or π^+ and (b) $B^0 \to \eta' K^0$. A likelihood analysis shows that the $B^+ \to \eta' h^+$ channel is dominated by $\eta' K^+$. (CLEO)

In summary, gluonic penguin decays have been established. Many decay modes have been observed for the first time and the emerging pattern is full of surprises. The observed penguin effects are large and while old favorites such as $B^0 \to \pi^+\pi^-$ might be less useful for CP-violation studies there is hope that new opportunities will open up.

Outlook: With the next Fermilab collider run still years away and LEP running at higher energies it is not likely that the B-meson lifetimes presented in this edition will change substantially over the next two years. Nor should we expect many new results on b-hadron spectroscopy. In the short term, CLEO is still taking data and so is SLD. The SLD collaboration expects to collect half a million hadronic Z events. Combining this with the excellent resolution of the SLD vertex detector could push the sensitivity on B_s mixing up to $\Delta m_s = 15\ \text{ps}^{-1}$. We have just began to observe rare B decays and already now we see many intriguing patterns: Why is $B \to \eta' K$ so large? Where are the $B^0 \to \pi^+\pi^-$ events? The size of the CLEO data sample will soon reach the $10\ \text{fb}^{-1}$ mark and many results, answers and new questions should be expected.

In the long term, which is actually only a year away, the next generation of B experiments will come on line: BaBar, BELLE, CLEO III, as well as HERA-B. So there is hope that in two years when the next edition of this *Review* will be written we have reached another milestone in our understanding of B mesons and b baryons.

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$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

See also the $B^{\pm}/B^0$ ADMIXTURE and $B^{\pm}/B^0/B_s^0/b$-baryon ADMIXTURE sections.

$B^{\pm}$ MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B_s^0}$, and $(m_{B_s^0} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B_s^0}$, and the mass differences.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5278.9 ± 1.8 OUR FIT					
5278.9 ± 1.5 OUR AVERAGE					
$5279.1 \pm 1.7 \pm 1.4$	147	[1] ABE	96B	CDF	$p\overline{p}$ at 1.8 TeV
$5278.8 \pm 0.54 \pm 2.0$	362	[2] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
$5278.3 \pm 0.4 \pm 2.0$		[2] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$5280.5 \pm 1.0 \pm 2.0$		[2,3] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$5278.6 \pm 0.8 \pm 2.0$		[2] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5275.8 \pm 1.3 \pm 3.0$	32	ALBRECHT	87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$5278.2 \pm 1.8 \pm 3.0$	12	[4] ALBRECHT	87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[1] Excluded from fit because it is not independent of ABE 96B B_s^0 mass and B_s^0-B mass difference.

[2] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average. See "Treatment of Errors" section of the Introductory Text. These experiments actually measure the difference between half of E_{cm} and the B mass.

[3] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.

[4] Found using fully reconstructed decays with $J/\psi(1S)$. ALBRECHT 87D assume $m_{\Upsilon(4S)} = 10577$ MeV.

$B^{\pm}$ MEAN LIFE

See $B^{\pm}/B^0/B_s^0/b$-baryon ADMIXTURE section for data on B-hadron mean life averaged over species of bottom particles.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.65 ± 0.04 OUR EVALUATION					
$1.68 \pm 0.07 \pm 0.02$		[5] ABE	98B	CDF	$p\overline{p}$ at 1.8 TeV
$1.66 \pm 0.06 \pm 0.05$		[6] ABE	97J	SLD	$e^+e^- \rightarrow Z$
$1.56 \pm 0.13 \pm 0.06$		[7] ABE	96C	CDF	$p\overline{p}$ at 1.8 TeV
$1.58 \pm 0.09 \pm 0.04$		[7] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.58^{+0.21}_{-0.18}{}^{+0.04}_{-0.03}$	94	[5] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.61 \pm 0.16 \pm 0.12$		[7,8] ABREU	95Q	DLPH	$e^+e^- \rightarrow Z$
$1.72 \pm 0.08 \pm 0.06$		[9] ADAM	95	DLPH	$e^+e^- \rightarrow Z$
$1.52 \pm 0.14 \pm 0.09$		[7] AKERS	95T	OPAL	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.58 \pm 0.09 \pm 0.03$		[10] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
1.70 ± 0.09		[11] ADAM	95	DLPH	$e^+e^- \rightarrow Z$
$1.61 \pm 0.16 \pm 0.05$	148	[5] ABE	94D	CDF	Repl. by ABE 98B
$1.30^{+0.33}_{-0.29} \pm 0.16$	92	[7] ABREU	93D	DLPH	Sup. by ABREU 95Q
$1.56 \pm 0.19 \pm 0.13$	134	[9] ABREU	93G	DLPH	Sup. by ADAM 95
$1.51^{+0.30}_{-0.28}{}^{+0.12}_{-0.14}$	59	[7] ACTON	93C	OPAL	Sup. by AKERS 95T
$1.47^{+0.22}_{-0.19}{}^{+0.15}_{-0.14}$	77	[7] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96J

[5] Measured mean life using fully reconstructed decays.

[6] Data analyzed using charge of secondary vertex.

[7] Data analyzed using $D/D^* \ell X$ event vertices.

[8] ABREU 95Q assumes $B(B^0 \rightarrow D^{**-} \ell^+ \nu_\ell) = 3.2 \pm 1.7\%$.

[9] Data analyzed using vertex-charge technique to tag B charge.

[10] Combined result of $D/D^* \ell X$ analysis and fully reconstructed B analysis.

[11] Combined ABREU 95Q and ADAM 95 result.

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^{\pm}/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

Semileptonic and leptonic modes

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\ell^+\nu_\ell$ anything	[a] (10.3 ± 0.9) %	
Γ_2	$\overline{D}^0\ell^+\nu_\ell$	[a] (1.86 ± 0.33) %	
Γ_3	$\overline{D}^*(2007)^0\ell^+\nu_\ell$	[a] (5.3 ± 0.8) %	
Γ_4	$\pi^0 e^+\nu_e$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_5	$\omega\ell^+\nu_\ell$	[a] $< 2.1 \times 10^{-4}$	CL=90%
Γ_6	$\omega\mu^+\nu_\mu$		
Γ_7	$\rho^0\ell^+\nu_\ell$	[a] $< 2.1 \times 10^{-4}$	CL=90%
Γ_8	$e^+\nu_e$	$< 1.5 \times 10^{-5}$	CL=90%
Γ_9	$\mu^+\nu_\mu$	$< 2.1 \times 10^{-5}$	CL=90%
Γ_{10}	$\tau^+\nu_\tau$	$< 5.7 \times 10^{-4}$	CL=90%
Γ_{11}	$e^+\nu_e\gamma$	$< 2.0 \times 10^{-4}$	CL=90%
Γ_{12}	$\mu^+\nu_\mu\gamma$	$< 5.2 \times 10^{-5}$	CL=90%

D, D^*, or D_s modes

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{13}	$\overline{D}^0\pi^+$	$(5.3 \pm 0.5) \times 10^{-3}$	
Γ_{14}	$\overline{D}^0\rho^+$	(1.34 ± 0.18) %	
Γ_{15}	$\overline{D}^0\pi^+\pi^+\pi^-$	(1.1 ± 0.4) %	
Γ_{16}	$\overline{D}^0\pi^+\pi^+\pi^-$ nonresonant	$(5 \pm 4) \times 10^{-3}$	
Γ_{17}	$\overline{D}^0\pi^+\rho^0$	$(4.2 \pm 3.0) \times 10^{-3}$	
Γ_{18}	$\overline{D}^0 a_1(1260)^+$	$(5 \pm 4) \times 10^{-3}$	
Γ_{19}	$D^*(2010)^-\pi^+\pi^+$	$(2.1 \pm 0.6) \times 10^{-3}$	
Γ_{20}	$D^-\pi^+\pi^+$	$< 1.4 \times 10^{-3}$	CL=90%
Γ_{21}	$\overline{D}^*(2007)^0\pi^+$	$(4.6 \pm 0.4) \times 10^{-3}$	
Γ_{22}	$D^*(2010)^+\pi^0$	$< 1.7 \times 10^{-4}$	CL=90%
Γ_{23}	$\overline{D}^*(2007)^0\rho^+$	(1.55 ± 0.31) %	
Γ_{24}	$\overline{D}^*(2007)^0\pi^+\pi^+\pi^-$	$(9.4 \pm 2.6) \times 10^{-3}$	
Γ_{25}	$\overline{D}^*(2007)^0 a_1(1260)^+$	(1.9 ± 0.5) %	
Γ_{26}	$D^*(2010)^-\pi^+\pi^+\pi^0$	(1.5 ± 0.7) %	
Γ_{27}	$D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$	< 1 %	CL=90%
Γ_{28}	$\overline{D}_1^*(2420)^0\pi^+$	$(1.5 \pm 0.6) \times 10^{-3}$	S=1.3
Γ_{29}	$\overline{D}_1^*(2420)^0\rho^+$	$< 1.4 \times 10^{-3}$	CL=90%
Γ_{30}	$\overline{D}_2^*(2460)^0\pi^+$	$< 1.3 \times 10^{-3}$	CL=90%
Γ_{31}	$\overline{D}_2^*(2460)^0\rho^+$	$< 4.7 \times 10^{-3}$	CL=90%
Γ_{32}	$\overline{D}^0 D_s^+$	(1.3 ± 0.4) %	
Γ_{33}	$\overline{D}^0 D_s^{*+}$	$(9 \pm 4) \times 10^{-3}$	
Γ_{34}	$\overline{D}^*(2007)^0 D_s^+$	(1.2 ± 0.5) %	
Γ_{35}	$\overline{D}^*(2007)^0 D_s^{*+}$	(2.7 ± 1.0) %	
Γ_{36}	$D_s^+\pi^0$	$< 2.0 \times 10^{-4}$	CL=90%
Γ_{37}	$D_s^{*+}\pi^0$	$< 3.3 \times 10^{-4}$	CL=90%
Γ_{38}	$D_s^+\eta$	$< 5 \times 10^{-4}$	CL=90%
Γ_{39}	$D_s^{*+}\eta$	$< 8 \times 10^{-4}$	CL=90%
Γ_{40}	$D_s^+\rho^0$	$< 4 \times 10^{-4}$	CL=90%
Γ_{41}	$D_s^{*+}\rho^0$	$< 5 \times 10^{-4}$	CL=90%
Γ_{42}	$D_s^+\omega$	$< 5 \times 10^{-4}$	CL=90%
Γ_{43}	$D_s^{*+}\omega$	$< 7 \times 10^{-4}$	CL=90%
Γ_{44}	$D_s^+ a_1(1260)^0$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_{45}	$D_s^{*+} a_1(1260)^0$	$< 1.6 \times 10^{-3}$	CL=90%
Γ_{46}	$D_s^+\phi$	$< 3.2 \times 10^{-4}$	CL=90%
Γ_{47}	$D_s^{*+}\phi$	$< 4 \times 10^{-4}$	CL=90%
Γ_{48}	$D_s^+\overline{K}^0$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{49}	$D_s^{*+}\overline{K}^0$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{50}	$D_s^+\overline{K}^*(892)^0$	$< 5 \times 10^{-4}$	CL=90%
Γ_{51}	$D_s^{*+}\overline{K}^*(892)^0$	$< 4 \times 10^{-4}$	CL=90%
Γ_{52}	$D_s^-\pi^+K^+$	$< 8 \times 10^{-4}$	CL=90%
Γ_{53}	$D_s^{*-}\pi^+K^+$	$< 1.2 \times 10^{-3}$	CL=90%
Γ_{54}	$D_s^-\pi^+K^*(892)^+$	$< 6 \times 10^{-3}$	CL=90%
Γ_{55}	$D_s^{*-}\pi^+K^*(892)^+$	$< 8 \times 10^{-3}$	CL=90%

Charmonium modes

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{56}	$J/\psi(1S)K^+$	$(9.9 \pm 1.0) \times 10^{-4}$	
Γ_{57}	$J/\psi(1S)K^+\pi^+\pi^-$	$(1.4 \pm 0.6) \times 10^{-3}$	
Γ_{58}	$J/\psi(1S)K^*(892)^+$	$(1.47 \pm 0.27) \times 10^{-3}$	
Γ_{59}	$J/\psi(1S)\pi^+$	$(5.0 \pm 1.5) \times 10^{-5}$	
Γ_{60}	$J/\psi(1S)\rho^+$	$< 7.7 \times 10^{-4}$	CL=90%
Γ_{61}	$J/\psi(1S)a_1(1260)^+$	$< 1.2 \times 10^{-3}$	CL=90%
Γ_{62}	$\psi(2S)K^+$	$(6.9 \pm 3.1) \times 10^{-4}$	S=1.3
Γ_{63}	$\psi(2S)K^*(892)^+$	$< 3.0 \times 10^{-3}$	CL=90%
Γ_{64}	$\psi(2S)K^+\pi^+\pi^-$	$(1.9 \pm 1.2) \times 10^{-3}$	
Γ_{65}	$\chi_{c1}(1P)K^+$	$(1.0 \pm 0.4) \times 10^{-3}$	
Γ_{66}	$\chi_{c1}(1P)K^*(892)^+$	$< 2.1 \times 10^{-3}$	CL=90%

K or K^* modes

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{67}	$K^0\pi^+$	$(2.3 \pm 1.1) \times 10^{-5}$	
Γ_{68}	$K^+\pi^0$	$< 1.6 \times 10^{-5}$	CL=90%
Γ_{69}	$\eta' K^+$	$(6.5 \pm 1.7) \times 10^{-5}$	
Γ_{70}	$\eta' K^*(892)^+$	$< 1.3 \times 10^{-4}$	CL=90%
Γ_{71}	ηK^+	$< 1.4 \times 10^{-5}$	CL=90%
Γ_{72}	$\eta K^*(892)^+$	$< 3.0 \times 10^{-5}$	CL=90%
Γ_{73}	$K^*(892)^0\pi^+$	$< 4.1 \times 10^{-5}$	CL=90%
Γ_{74}	$K^*(892)^+\pi^0$	$< 9.9 \times 10^{-5}$	CL=90%
Γ_{75}	$K^+\pi^-\pi^+$ nonresonant	$< 2.8 \times 10^{-5}$	CL=90%
Γ_{76}	$K^-\pi^+\pi^+$ nonresonant	$< 5.6 \times 10^{-5}$	CL=90%
Γ_{77}	$K_1(1400)^0\pi^+$	$< 2.6 \times 10^{-3}$	CL=90%
Γ_{78}	$K_2^*(1430)^0\pi^+$	$< 6.8 \times 10^{-4}$	CL=90%
Γ_{79}	$K^+\rho^0$	$< 1.9 \times 10^{-5}$	CL=90%
Γ_{80}	$K^0\rho^+$	$< 4.8 \times 10^{-5}$	CL=90%
Γ_{81}	$K^*(892)^+\pi^+\pi^-$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{82}	$K^*(892)^+\rho^0$	$< 9.0 \times 10^{-4}$	CL=90%
Γ_{83}	$K_1(1400)^+\rho^0$	$< 7.8 \times 10^{-4}$	CL=90%
Γ_{84}	$K_2^*(1430)^+\rho^0$	$< 1.5 \times 10^{-3}$	CL=90%
Γ_{85}	$K^+\overline{K}^0$	$< 2.1 \times 10^{-5}$	CL=90%
Γ_{86}	$K^+K^-\pi^+$ nonresonant	$< 7.5 \times 10^{-5}$	CL=90%
Γ_{87}	$K^+K^-K^+$	$< 2.0 \times 10^{-4}$	CL=90%
Γ_{88}	$K^+\phi$	$< 1.2 \times 10^{-5}$	CL=90%
Γ_{89}	$K^+K^-K^+$ nonresonant	$< 3.8 \times 10^{-5}$	CL=90%
Γ_{90}	$K^*(892)^+K^+K^-$	$< 1.6 \times 10^{-3}$	CL=90%
Γ_{91}	$K^*(892)^+\phi$	$< 7.0 \times 10^{-5}$	CL=90%
Γ_{92}	$K_1(1400)^+\phi$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{93}	$K_2^*(1430)^+\phi$	$< 3.4 \times 10^{-3}$	CL=90%
Γ_{94}	$K^+f_0(980)$	$< 8 \times 10^{-5}$	CL=90%
Γ_{95}	$K^*(892)^+\gamma$	$(5.7 \pm 3.3) \times 10^{-5}$	
Γ_{96}	$K_1(1270)^+\gamma$	$< 7.3 \times 10^{-3}$	CL=90%
Γ_{97}	$K_1(1400)^+\gamma$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_{98}	$K_2^*(1430)^+\gamma$	$< 1.4 \times 10^{-3}$	CL=90%
Γ_{99}	$K^*(1680)^+\gamma$	$< 1.9 \times 10^{-3}$	CL=90%
Γ_{100}	$K_3^*(1780)^+\gamma$	$< 5.5 \times 10^{-3}$	CL=90%
Γ_{101}	$K_4^*(2045)^+\gamma$	$< 9.9 \times 10^{-3}$	CL=90%

Light unflavored meson modes

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{102}	$\pi^+\pi^0$	$< 2.0 \times 10^{-5}$	CL=90%
Γ_{103}	$\pi^+\pi^+\pi^-$	$< 1.3 \times 10^{-4}$	CL=90%
Γ_{104}	$\rho^0\pi^+$	$< 4.3 \times 10^{-5}$	CL=90%
Γ_{105}	$\pi^+f_0(980)$	$< 1.4 \times 10^{-4}$	CL=90%
Γ_{106}	$\pi^+f_2(1270)$	$< 2.4 \times 10^{-4}$	CL=90%
Γ_{107}	$\pi^+\pi^-\pi^+$ nonresonant	$< 4.1 \times 10^{-5}$	CL=90%
Γ_{108}	$\pi^+\pi^0\pi^0$	$< 8.9 \times 10^{-4}$	CL=90%
Γ_{109}	$\rho^+\pi^0$	$< 7.7 \times 10^{-5}$	CL=90%
Γ_{110}	$\pi^+\pi^-\pi^+\pi^0$	$< 4.0 \times 10^{-3}$	CL=90%
Γ_{111}	$\rho^+\rho^0$	$< 1.0 \times 10^{-3}$	CL=90%
Γ_{112}	$a_1(1260)^+\pi^0$	$< 1.7 \times 10^{-3}$	CL=90%
Γ_{113}	$a_1(1260)^0\pi^+$	$< 9.0 \times 10^{-4}$	CL=90%
Γ_{114}	$\omega\pi^+$	$< 4.0 \times 10^{-4}$	CL=90%
Γ_{115}	$\eta\pi^+$	$< 1.5 \times 10^{-5}$	CL=90%
Γ_{116}	$\eta'\pi^+$	$< 3.1 \times 10^{-5}$	CL=90%

Γ_{117}	$\eta' \rho^+$	$< 4.7 \times 10^{-5}$	CL=90%
Γ_{118}	$\eta \rho^+$	$< 3.2 \times 10^{-5}$	CL=90%
Γ_{119}	$\pi^+\pi^+\pi^+\pi^-\pi^-$	$< 8.6 \times 10^{-4}$	CL=90%
Γ_{120}	$\rho^0 a_1(1260)^+$	$< 6.2 \times 10^{-4}$	CL=90%
Γ_{121}	$\rho^0 a_2(1320)^+$	$< 7.2 \times 10^{-4}$	CL=90%
Γ_{122}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	$< 6.3 \times 10^{-3}$	CL=90%
Γ_{123}	$a_1(1260)^+ a_1(1260)^0$	< 1.3 %	CL=90%

Baryon modes

Γ_{124}	$p\overline{p}\pi^+$	$< 1.6 \times 10^{-4}$	CL=90%
Γ_{125}	$p\overline{p}\pi^+$ nonresonant	$< 5.3 \times 10^{-5}$	CL=90%
Γ_{126}	$p\overline{p}\pi^+\pi^+\pi^-$	$< 5.2 \times 10^{-4}$	CL=90%
Γ_{127}	$p\overline{p}K^+$ nonresonant	$< 8.9 \times 10^{-5}$	CL=90%
Γ_{128}	$p\overline{\Lambda}$	$< 6 \times 10^{-5}$	CL=90%
Γ_{129}	$p\overline{\Lambda}\pi^+\pi^-$	$< 2.0 \times 10^{-4}$	CL=90%
Γ_{130}	$\overline{\Delta}^0 p$	$< 3.8 \times 10^{-4}$	CL=90%
Γ_{131}	$\Delta^{++}\overline{p}$	$< 1.5 \times 10^{-4}$	CL=90%
Γ_{132}	$\Lambda_c^- p\pi^+$	$(6.2 \pm 2.7) \times 10^{-4}$	
Γ_{133}	$\Lambda_c^- p\pi^+\pi^0$	$< 3.12 \times 10^{-3}$	CL=90%
Γ_{134}	$\Lambda_c^- p\pi^+\pi^+\pi^-$	$< 1.46 \times 10^{-3}$	CL=90%
Γ_{135}	$\Lambda_c^- p\pi^+\pi^+\pi^-\pi^0$	< 1.34 %	CL=90%

Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

Γ_{136}	$\pi^+ e^+ e^-$	*B1*	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{137}	$\pi^+ \mu^+ \mu^-$	*B1*	$< 9.1 \times 10^{-3}$	CL=90%
Γ_{138}	$K^+ e^+ e^-$	*B1*	$< 6 \times 10^{-5}$	CL=90%
Γ_{139}	$K^+ \mu^+ \mu^-$	*B1*	$< 1.0 \times 10^{-5}$	CL=90%
Γ_{140}	$K^*(892)^+ e^+ e^-$	*B1*	$< 6.9 \times 10^{-4}$	CL=90%
Γ_{141}	$K^*(892)^+ \mu^+ \mu^-$	*B1*	$< 1.2 \times 10^{-3}$	CL=90%
Γ_{142}	$\pi^+ e^+ \mu^-$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{143}	$\pi^+ e^- \mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{144}	$K^+ e^+ \mu^-$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{145}	$K^+ e^- \mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{146}	$\pi^- e^+ e^+$	*L*	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{147}	$\pi^- \mu^+ \mu^+$	*L*	$< 9.1 \times 10^{-3}$	CL=90%
Γ_{148}	$\pi^- e^+ \mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%
Γ_{149}	$K^- e^+ e^+$	*L*	$< 3.9 \times 10^{-3}$	CL=90%
Γ_{150}	$K^- \mu^+ \mu^+$	*L*	$< 9.1 \times 10^{-3}$	CL=90%
Γ_{151}	$K^- e^+ \mu^+$	*LF*	$< 6.4 \times 10^{-3}$	CL=90%

[a] An ℓ indicates an e or a μ mode, not a sum over these modes.

B^+ BRANCHING RATIOS

$\Gamma(\ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1025±0.0057±0.0065	[12] ARTUSO	97	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID		TECN	COMMENT
0.101 ±0.018 ±0.015	ATHANAS	94	CLE2	Sup. by ARTUSO 97

[12] ARTUSO 97 uses partial reconstruction of $B \to D^* \ell \nu_\ell$ and inclusive semileptonic branching ratio from BARISH 96B (0.1049 ± 0.0017 ± 0.0043).

$\Gamma(\overline{D}^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_2/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0186±0.0033 OUR AVERAGE				
0.0194±0.0015±0.0034	[13] ATHANAS	97	CLE2	$e^+e^- \to \Upsilon(4S)$
0.016 ±0.006 ±0.003	[14] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[13] ATHANAS 97 uses missing energy and missing momentum to reconstruct neutrino.

[14] FULTON 91 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at the $\Upsilon(4S)$.

$\Gamma(\overline{D}^*(2007)^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_3/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.053 ±0.008 OUR AVERAGE					
0.0513±0.0054±0.0064	302	[15] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$
0.066 ±0.016 ±0.015		[16] ALBRECHT	92C	ARG	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	398	[17] SANGHERA	93	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.041 \pm 0.008 {}^{+0.008}_{-0.009}$		[18] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.018 ±0.014		[19] ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$

[15] BARISH 95 use B($D^0 \to K^-\pi^+$) = (3.91 ± 0.08 ± 0.17)% and B($D^{*0} \to D^0\pi^0$) = (63.6 ± 2.3 ± 3.3)%.

[16] ALBRECHT 92C reports 0.058 ± 0.014 ± 0.013. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$). Assumes equal production of $B^0\overline{B}^0$ and B^+B^- at the $\Upsilon(4S)$.

[17] Combining $\overline{D}^{*0}\ell^+\nu_\ell$ and $\overline{D}^{*-}\ell^+\nu_\ell$ SANGHERA 93 test $V-A$ structure and fit the decay angular distributions to obtain $A_{FB} = 3/4*(\Gamma^- - \Gamma^+)/\Gamma = 0.14 \pm 0.06 \pm 0.03$. Assuming a value of V_{cb}, they measure V, A_1, and A_2, the three form factors for the $D^*\ell\nu_\ell$ decay, where results are slightly dependent on model assumptions.

[18] Assumes equal production of $B^0\overline{B}^0$ and B^+B^- at the $\Upsilon(4S)$. Uncorrected for D and D^* branching ratio assumptions.

[19] ANTREASYAN 90B is average over B and $\overline{D}^*(2010)$ charge states.

$\Gamma(\pi^0 e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\omega \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_5/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<2.1 \times 10^{-4}}$	90	[20] BEAN	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[20] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\rho^0\ell^+\nu_\ell)$ and $\Gamma(\rho^-\ell^+\nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \to \omega\ell^+\nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| < 0.8\text{–}0.13$ at 90% CL is derived as well.

$\Gamma(\omega \mu^+ \nu_\mu)/\Gamma_{\text{total}}$ — Γ_6/Γ

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID		TECN
seen	[21] ALBRECHT	91C	ARG

[21] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \to u$ transition.

$\Gamma(\rho^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_7/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<2.1 \times 10^{-4}}$	90	[22] BEAN	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[22] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\omega^0\ell^+\nu_\ell)$ and $\Gamma(\rho^-\ell^+\nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \to \rho^0\ell^+\nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| < 0.8\text{–}0.13$ at 90% CL is derived as well.

$\Gamma(e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<1.5 \times 10^{-5}}$	90	ARTUSO	95	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\mu^+ \nu_\mu)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<2.1 \times 10^{-5}}$	90	ARTUSO	95	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\tau^+ \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<5.7 \times 10^{-4}}$	90	[23] ACCIARRI	97F	L3	$e^+e^- \to Z$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.04 \times 10^{-2}$	90	[24] ALBRECHT	95D	ARG	$e^+e^- \to \Upsilon(4S)$
$<2.2 \times 10^{-3}$	90	ARTUSO	95	CLE2	$e^+e^- \to \Upsilon(4S)$
$<1.8 \times 10^{-3}$	90	[25] BUSKULIC	95	ALEP	$e^+e^- \to Z$

[23] ACCIARRI 97F uses missing-energy technique and $f(b \to B^-) = (38.2 \pm 2.5)\%$.

[24] ALBRECHT 95D use full reconstruction of one B decay as tag.

[25] BUSKULIC 95 uses same missing-energy technique as in $\overline{b} \to \tau^+\nu_\tau X$, but analysis is restricted to endpoint region of missing-energy distribution.

$\Gamma(e^+ \nu_e \gamma)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<2.0 \times 10^{-4}}$	90	[26] BROWDER	97	CLE2	$e^+e^- \to \Upsilon(4S)$

[26] BROWDER 97 uses the hermiticity of the CLEO II detector to reconstruct the neutrino energy and momentum.

$\Gamma(\mu^+ \nu_\mu \gamma)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<5.2 \times 10^{-5}}$	90	[27] BROWDER	97	CLE2	$e^+e^- \to \Upsilon(4S)$

[27] BROWDER 97 uses the hermiticity of the CLEO II detector to reconstruct the neutrino energy and momentum.

$\Gamma(\overline{D}^0 \pi^+)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0053±0.0005 OUR AVERAGE					
0.0055±0.0004±0.0005	304	[28] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0050±0.0007±0.0006	54	[29] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.0054 {}^{+0.0018}_{-0.0015} {}^{+0.0012}_{-0.0009}$	14	[30] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0020±0.0008±0.0006	12	[29] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
0.0019±0.0010±0.0006	7	[31] ALBRECHT	88K	ARG	$e^+e^- \to \Upsilon(4S)$

[28] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[29] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.

[30] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[31] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55. Superseded by ALBRECHT 90J.

$\Gamma(\overline{D}^0 \rho^+)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0134±0.0018 OUR AVERAGE				
0.0135±0.0012±0.0015	212	[32] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.013 ±0.004 ±0.004	19	[33] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.021 ±0.008 ±0.009	10	[34] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[32] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[33] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.

[34] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55.

$\Gamma(\overline{D}^0 \pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{15}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0115±0.0029±0.0021	[35] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[35] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+\pi^+\pi^-$ nonresonant$)/\Gamma_{\rm total}$ Γ_{16}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0051±0.0034±0.0023	[36] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[36] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+\rho^0)/\Gamma_{\rm total}$ Γ_{17}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0042±0.0023±0.0020	[37] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[37] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 a_1(1260)^+)/\Gamma_{\rm total}$ Γ_{18}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0045±0.0019±0.0031	[38] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[38] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^-\pi^+\pi^+)/\Gamma_{\rm total}$ Γ_{19}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0021±0.0006 OUR AVERAGE					
0.0019±0.0007±0.0003		14	[39] ALAM 94′	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0026±0.0014±0.0007		11	[40] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0024^{+0.0017}_{-0.0016}{}^{+0.0010}_{-0.0006}$		3	[41] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.004	90		[42] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.005 ±0.002 ±0.003		7	[43] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$

[39] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[40] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.

[41] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[42] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$. The authors also find the product branching fraction into $D^{**}\pi$ followed by $D^{**} \to D^*(2010)\pi$ to be $0.0014^{+0.0008}_{-0.0006} \pm 0.0003$ where D^{**} represents all orbitally excited D mesons.

[43] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume B($\Upsilon(4S) \to B^+B^-$) = 55% and B($\Upsilon(4S) \to B^0\overline{B}^0$) = 45%. Superseded by ALBRECHT 90J.

$\Gamma(D^-\pi^+\pi^+)/\Gamma_{\rm total}$ Γ_{20}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0014	90		[44] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.007	90		[45] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.0025^{+0.0041}_{-0.0023}{}^{+0.0024}_{-0.0008}$		1	[46] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[44] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \to K^-\pi^+\pi^+$).

[45] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$ followed by $D_0^*(2340) \to D\pi$ is < 0.005 at 90%CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \to D\pi$ is < 0.004 at 90%CL.

[46] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. B($D^- \to K^+\pi^-\pi^-$) = (9.1 ± 1.3 ± 0.4)% is assumed.

$\Gamma(\overline{D}^*(2007)^0\pi^+)/\Gamma_{\rm total}$ Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0046 ±0.0004 OUR AVERAGE				
0.00434±0.00047±0.00018		[47] BRANDENB... 98	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0052 ±0.0007 ±0.0007	71	[48] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0072 ±0.0018 ±0.0016		[49] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0040 ±0.0014 ±0.0012	9	[49] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0027 ±0.0044		[50] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[47] BRANDENBURG 98 assume equal production of B^+ and B^0 at $\Upsilon(4S)$ and use the D^* reconstruction technique. The first error is their experiment's error and the second error is the systematic error from the PDG 96 value of B($D^* \to D\pi$).

[48] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \to D^0\pi^0$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[49] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

[50] This is a derived branching ratio, using the inclusive pion spectrum and other two-body B decays. BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(D^*(2010)^+\pi^0)/\Gamma_{\rm total}$ Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00017	90	[51] BRANDENB... 98	CLE2	$e^+e^- \to \Upsilon(4S)$

[51] BRANDENBURG 98 assume equal production of B^+ and B^0 at $\Upsilon(4S)$ and use the D^* partial reconstruction technique. The first error is their experiment's error and the second error is the systematic error from the PDG 96 value of B($D^* \to D\pi$).

$\Gamma(\overline{D}^*(2007)^0\rho^+)/\Gamma_{\rm total}$ Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0155±0.0031 OUR AVERAGE				
0.0168±0.0021±0.0028	86	[52] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.010 ±0.006 ±0.004	7	[53] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[52] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \to D^0\pi^0$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$). The nonresonant $\pi^+\pi^0$ contribution under the ρ^+ is negligible.

[53] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(\overline{D}^*(2007)^0\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{24}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0094±0.0020±0.0017	48	[54,55] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[54] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \to D^0\pi^0$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[55] The three pion mass is required to be between 1.0 and 1.6 GeV consistent with an a_1 meson. (If this channel is dominated by a_1^+, the branching ratio for $\overline{D}^{*0}a_1^+$ is twice that for $\overline{D}^{*0}\pi^+\pi^+\pi^-$.)

$\Gamma(\overline{D}^*(2007)^0 a_1(1260)^+)/\Gamma_{\rm total}$ Γ_{25}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0188±0.0040±0.0034	[56,57] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[56] ALAM 94 value is twice their $\Gamma(\overline{D}^*(2007)^0\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ value based on their observation that the three pions are dominantly in the $a_1(1260)$ mass range 1.0 to 1.6 GeV.

[57] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \to D^0\pi^0$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^0)/\Gamma_{\rm total}$ Γ_{26}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0150±0.0070±0.0003	26	[58] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.043 ±0.013 ±0.026	24	[59] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$

[58] ALBRECHT 90J reports 0.018 ± 0.007 ± 0.005 for B($D^*(2010)^+ \to D^0\pi^+$) = 0.57 ± 0.06. We rescale to our best value B($D^*(2010)^+ \to D^0\pi^+$) = $(68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[59] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume B($\Upsilon(4S) \to B^+B^-$) = 55% and B($\Upsilon(4S) \to B^0\overline{B}^0$) = 45%. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	[60] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[60] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(\overline{D}_1^*(2420)^0\pi^+)/\Gamma_{\text{total}}$ — Γ_{28}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0015±0.0006 OUR AVERAGE		Error includes scale factor of 1.3.		
0.0011±0.0005±0.0002	8	[61] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0025±0.0007±0.0006		[62] ALBRECHT 94D	ARG	$e^+e^- \to \Upsilon(4S)$

[61] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and assuming B($D_1(2420)^0 \to D^*(2010)^+\pi^-$) = 67%.

[62] ALBRECHT 94D assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) assuming B($D_1(2420)^0 \to D^*(2010)^+\pi^-$) = 67%.

$\Gamma(\overline{D}_1^*(2420)^0\rho^+)/\Gamma_{\text{total}}$ — Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0014	90	[63] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[63] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) assuming B($D_1(2420)^0 \to D^*(2010)^+\pi^-$) = 67%.

$\Gamma(\overline{D}_2^*(2460)^0\pi^+)/\Gamma_{\text{total}}$ — Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[64] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0028	90	[65] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
<0.0023	90	[66] ALBRECHT 94D	ARG	$e^+e^- \to \Upsilon(4S)$

[64] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \to K^-\pi^+\pi^+$) and B($D_2^*(2460)^0 \to D^+\pi^-$) = 30%.

[65] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \to K^-\pi^+\pi^+$), the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and B($D_2^*(2460)^0 \to D^*(2010)^+\pi^-$) = 20%.

[66] ALBRECHT 94D assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and B($D_2^*(2460)^0 \to D^*(2010)^+\pi^-$) = 30%.

$\Gamma(\overline{D}_2^*(2460)^0\rho^+)/\Gamma_{\text{total}}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0047	90	[67] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
<0.005	90	[68] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[67] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \to K^-\pi^+\pi^+$) and B($D_2^*(2460)^0 \to D^+\pi^-$) = 30%.

[68] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \to K^-\pi^+\pi^+$), the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and B($D_2^*(2460)^0 \to D^*(2010)^+\pi^-$) = 20%.

$\Gamma(\overline{D}^0 D_s^+)/\Gamma_{\text{total}}$ — Γ_{32}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.013 ±0.004 OUR AVERAGE				
$0.0122\pm0.0032^{+0.0029}_{-0.0030}$		[69] GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
0.018 ±0.009 ±0.004		[70] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.016 ±0.007 ±0.004	5	[71] BORTOLETTO 90	CLEO	$e^+e^- \to \Upsilon(4S)$

[69] GIBAUT 96 reports 0.0126 ± 0.0022 ± 0.0025 for B($D_s^+ \to \phi\pi^+$) = 0.035. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[70] ALBRECHT 92G reports 0.024 ± 0.012 ± 0.004 for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 branching ratios, e.g., B($D^0 \to K^-\pi^+$) = 3.71 ± 0.25%.

[71] BORTOLETTO 90 reports 0.029 ± 0.013 for B($D_s^+ \to \phi\pi^+$) = 0.02. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{D}^0 D_s^{*+})/\Gamma_{\text{total}}$ — Γ_{33}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.009 ±0.004 OUR AVERAGE			
$0.0084\pm0.0031^{+0.0020}_{-0.0021}$	[72] GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
0.012 ±0.009 ±0.003	[73] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$

[72] GIBAUT 96 reports 0.0087 ± 0.0027 ± 0.0017 for B($D_s^+ \to \phi\pi^+$) = 0.035. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[73] ALBRECHT 92G reports 0.016 ± 0.012 ± 0.003 for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 branching ratios, e.g., B($D^0 \to K^-\pi^+$) = 3.71 ± 0.25%.

$\Gamma(\overline{D}^*(2007)^0 D_s^+)/\Gamma_{\text{total}}$ — Γ_{34}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.012±0.005 OUR AVERAGE			
0.014±0.005±0.003	[74] GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
0.010±0.007±0.002	[75] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$

[74] GIBAUT 96 reports 0.0140 ± 0.0043 ± 0.0035 for B($D_s^+ \to \phi\pi^+$) = 0.035. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[75] ALBRECHT 92G reports 0.013 ± 0.009 ± 0.002 for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 and $D^*(2007)^0$ branching ratios, e.g., B($D^0 \to K^-\pi^+$) = 3.71 ± 0.25% and B($D^*(2007)^0 \to D^0\pi^0$) = 55 ± 6%.

$\Gamma(\overline{D}^*(2007)^0 D_s^{*+})/\Gamma_{\text{total}}$ — Γ_{35}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.027±0.010 OUR AVERAGE			
0.030±0.011±0.007	[76] GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
0.023±0.013±0.006	[77] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$

[76] GIBAUT 96 reports 0.0310 ± 0.0088 ± 0.0065 for B($D_s^+ \to \phi\pi^+$) = 0.035. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[77] ALBRECHT 92G reports 0.031 ± 0.016 ± 0.005 for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 and $D^*(2007)^0$ branching ratios, e.g., B($D^0 \to K^-\pi^+$) = 3.71 ± 0.25% and B($D^*(2007)^0 \to D^0\pi^0$) = 55 ± 6%.

$\Gamma(D_s^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00020	90	[78] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[78] ALEXANDER 93B reports $< 2.0 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$[\Gamma(D_s^+\pi^0) + \Gamma(D_s^{*+}\pi^0)]/\Gamma_{\text{total}}$ — $(\Gamma_{36}+\Gamma_{37})/\Gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0007	90	[79] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[79] ALBRECHT 93E reports $< 0.9 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\pi^0)/\Gamma_{\text{total}}$ — Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00033	90	[80] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[80] ALEXANDER 93B reports $< 3.2 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\eta)/\Gamma_{\text{total}}$ — Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[81] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[81] ALEXANDER 93B reports $< 4.6 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\eta)/\Gamma_{\text{total}}$ — Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0008	90	[82] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[82] ALEXANDER 93B reports $< 7.5 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\rho^0)/\Gamma_{\text{total}}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0004	90	[83] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[83] ALEXANDER 93B reports $< 3.7 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$[\Gamma(D_s^+\rho^0) + \Gamma(D_s^+\overline{K}^*(892)^0)]/\Gamma_{\text{total}}$ — $(\Gamma_{40}+\Gamma_{50})/\Gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0025	90	[84] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[84] ALBRECHT 93E reports $< 3.4 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\rho^0)/\Gamma_{\text{total}}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[85] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[85] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$[\Gamma(D_s^{*+}\rho^0)+\Gamma(D_s^{*+}\overline{K}^*(892)^0)]/\Gamma_{\text{total}}$ $(\Gamma_{41}+\Gamma_{51})/\Gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0015	90	[86] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[86] ALBRECHT 93E reports $< 2.0 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\omega)/\Gamma_{\text{total}}$ Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[87] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0025	90	[88] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[87] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[88] ALBRECHT 93E reports $< 3.4 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\omega)/\Gamma_{\text{total}}$ Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0007	90	[89] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0014	90	[90] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[89] ALEXANDER 93B reports $< 6.8 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[90] ALBRECHT 93E reports $< 1.9 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+a_1(1260)^0)/\Gamma_{\text{total}}$ Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	[91] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[91] ALBRECHT 93E reports $< 3.0 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}a_1(1260)^0)/\Gamma_{\text{total}}$ Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0016	90	[92] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[92] ALBRECHT 93E reports $< 2.2 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\phi)/\Gamma_{\text{total}}$ Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00032	90	[93] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0013	90	[94] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[93] ALEXANDER 93B reports $< 3.1 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[94] ALBRECHT 93E reports $< 1.7 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\phi)/\Gamma_{\text{total}}$ Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0004	90	[95] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0016	90	[96] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[95] ALEXANDER 93B reports $< 4.2 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[96] ALBRECHT 93E reports $< 2.1 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\overline{K}^0)/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0011	90	[97] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0019	90	[98] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[97] ALEXANDER 93B reports $< 10.3 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[98] ALBRECHT 93E reports $< 2.5 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\overline{K}^0)/\Gamma_{\text{total}}$ Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0011	90	[99] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0023	90	[100] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[99] ALEXANDER 93B reports $< 10.9 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

[100] ALBRECHT 93E reports $< 3.1 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^+\overline{K}^*(892)^0)/\Gamma_{\text{total}}$ Γ_{50}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[101] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[101] ALEXANDER 93B reports $< 4.4 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\overline{K}^*(892)^0)/\Gamma_{\text{total}}$ Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0004	90	[102] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[102] ALEXANDER 93B reports $< 4.3 \times 10^{-4}$ for B($D_s^+ \to \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^-\pi^+K^+)/\Gamma_{\text{total}}$ Γ_{52}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0008	90	[103] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[103] ALBRECHT 93E reports $< 1.1 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*-}\pi^+K^+)/\Gamma_{\text{total}}$ Γ_{53}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0012	90	[104] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[104] ALBRECHT 93E reports $< 1.6 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^-\pi^+K^*(892)^+)/\Gamma_{\text{total}}$ Γ_{54}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	[105] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[105] ALBRECHT 93E reports $< 8.6 \times 10^{-3}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*-}\pi^+K^*(892)^+)/\Gamma_{\text{total}}$ Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.008	90	[106] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[106] ALBRECHT 93E reports $< 1.1 \times 10^{-2}$ for B($D_s^+ \to \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \to \phi\pi^+$) = 0.036.

$\Gamma(J/\psi(1S)K^+)/\Gamma_{\text{total}}$ Γ_{56}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
9.9 ± 1.0 OUR AVERAGE				
10.2 ± 0.8 ±0.7		[107] JESSOP 97	CLE2	$e^+e^- \to \Upsilon(4S)$
9.16± 3.01±0.30		[108] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
8.0 ± 3.5 ±0.3	6	[109] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11.0 ± 1.5 ±0.9	59	[110] ALAM 94	CLE2	Repl. by JESSOP 97
22 ±10 ±2		BUSKULIC 92G	ALEP	$e^+e^- \to Z$
7 ± 4	3	[111] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
10 ± 7 ±2	3	[112] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
9 ± 5	3	[113] ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[107] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[108] BORTOLETTO 92 reports 8 ± 2 ± 2 for B($J/\psi(1S) \to e^+e^-$) = 0.069 ± 0.009. We rescale to our best value B($J/\psi(1S) \to e^+e^-$) = $(6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[109] ALBRECHT 90J reports 7 ± 3 ± 1 for B($J/\psi(1S) \to e^+e^-$) = 0.069 ± 0.009. We rescale to our best value B($J/\psi(1S) \to e^+e^-$) = $(6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[110] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[111] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

[112] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[113] ALAM 86 assumes $B^\pm/B^0$ ratio is 60/40.

$\Gamma(J/\psi(1S)K^+\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{57}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0014 ± 0.0006 OUR AVERAGE					
$0.00137 \pm 0.00081 \pm 0.00004$			[114] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.00137 \pm 0.00090 \pm 0.00004$		6	[115] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0018	90		[116] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[114] BORTOLETTO 92 reports $0.0012 \pm 0.0006 \pm 0.0004$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[115] ALBRECHT 87D reports 0.0012 ± 0.0008 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. They actually report 0.0011 ± 0.0007 assuming $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. We rescale to 50/50. Analysis explicitly removes $B^+ \to \psi(2S)K^+$.

[116] ALBRECHT 90J reports < 0.0016 for $B(J/\psi(1S) \to e^+e^-) = 0.069$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = 0.0602$. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{58}/Γ

For polarization information see the Listings at the end of the "B^0 Branching Ratios" section.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.00147 ± 0.00027 OUR AVERAGE				
$0.00141 \pm 0.00023 \pm 0.00024$		[117] JESSOP 97	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.00158 \pm 0.00047 \pm 0.00027$		[118] ABE 96H	CDF	$p\overline{p}$ at 1.8 TeV
$0.00149 \pm 0.00107 \pm 0.00005$		[119] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.0018 \pm 0.0013 \pm 0.0001$	2	[120] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.00178 \pm 0.00051 \pm 0.00023$	13	[121] ALAM 94	CLE2	Sup. by JESSOP 97

[117] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[118] ABE 96H assumes that $B(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$.

[119] BORTOLETTO 92 reports $0.0013 \pm 0.0009 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[120] ALBRECHT 90J reports $0.0016 \pm 0.0011 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[121] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)K^*(892)^+)/\Gamma(J/\psi(1S)K^+)$ — Γ_{58}/Γ_{56}

VALUE	DOCUMENT ID	TECN	COMMENT
1.52 ± 0.24 OUR AVERAGE			
$1.45 \pm 0.20 \pm 0.17$	[122] JESSOP 97	CLE2	$e^+e^- \to \Upsilon(4S)$
$1.92 \pm 0.60 \pm 0.17$	ABE 96Q	CDF	$p\overline{p}$

[122] JESSOP 97 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$. The measurement is actually measured as an average over kaon charged and neutral states.

$\Gamma(J/\psi(1S)\pi^+)/\Gamma(J/\psi(1S)K^+)$ — Γ_{59}/Γ_{56}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.051 ± 0.014 OUR AVERAGE				
$0.05\ ^{+0.019}_{-0.017} \pm 0.001$		ABE 96R	CDF	$p\overline{p}$ 1.8 TeV
0.052 ± 0.024		BISHAI 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.043 ± 0.023	5	[123] ALEXANDER 95	CLE2	Sup. by BISHAI 96

[123] Assumes equal production of B^+B^- and $B^0\overline{B}^0$ on $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)\rho^+)/\Gamma_{\rm total}$ — Γ_{60}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-4}$	90	BISHAI 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(J/\psi(1S)a_1(1260)^+)/\Gamma_{\rm total}$ — Γ_{61}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-3}$	90	BISHAI 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\psi(2S)K^+)/\Gamma_{\rm total}$ — Γ_{62}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
6.9 ± 3.1 OUR AVERAGE Error includes scale factor of 1.3.					
$6.1 \pm 2.3 \pm 0.9$		7	[124] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
$18 \pm 8 \pm 4$		5	[124] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5	90		[124] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
22 ± 17		3	[125] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$

[124] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[125] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

$\Gamma(\psi(2S)K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{63}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0030	90	[126] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0035	90	[126] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.0049	90	[126] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[126] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^+\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0019 \pm 0.0011 \pm 0.0004$	3	[127] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[127] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^+)/\Gamma_{\rm total}$ — Γ_{65}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0010 ± 0.0004 OUR AVERAGE				
$0.00097 \pm 0.00040 \pm 0.00009$	6	[128] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.0019 \pm 0.0013 \pm 0.0006$		[129] ALBRECHT 92E	ARG	$e^+e^- \to \Upsilon(4S)$

[128] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[129] ALBRECHT 92E assumes no $\chi_{c2}(1P)$ production and $B(\Upsilon(4S) \to B^+B^-) = 50\%$.

$\Gamma(\chi_{c1}(1P)K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0021	90	[130] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[130] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(K^0\pi^+)/\Gamma_{\rm total}$ — Γ_{67}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
$2.3\ ^{+1.1}_{-1.0} \pm 0.36$		GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.8	90	ASNER 96	CLE2	Repl. by GODANG 98
<19	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
<10	90	[131] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<68	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[131] AVERY 89B reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^+\pi^0)/\Gamma_{\rm total}$ — Γ_{68}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.6 \times 10^{-5}$	90	GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.4 \times 10^{-5}$	90	ASNER 96	CLE2	Repl. by GODANG 98

$\left[\Gamma(K^+\pi^0) + \Gamma(\pi^+\pi^0)\right]/\Gamma_{\rm total}$ — $(\Gamma_{68}+\Gamma_{102})/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$(1.6\ ^{+0.6}_{-0.5} \pm 0.36) \times 10^{-5}$	GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta' K^+)/\Gamma_{\rm total}$ — Γ_{69}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$(6.5\ ^{+1.5}_{-1.4} \pm 0.9) \times 10^{-5}$	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta' K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{70}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-4}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta K^+)/\Gamma_{\rm total}$ — Γ_{71}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{72}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\pi^+)/\Gamma_{\rm total}$ — Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.1 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.9 \times 10^{-4}$	90	[132] ADAM 96D	DLPH	$e^+e^- \to Z$
$<4.8 \times 10^{-4}$	90	[133] ABREU 95N	DLPH	Sup. by ADAM 96D
$<1.7 \times 10^{-4}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.5 \times 10^{-4}$	90	[134] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2.6 \times 10^{-4}$	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[132] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[133] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[134] AVERY 89B reports $< 1.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\pi^0)/\Gamma_{\rm total}$ — Γ_{74}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.9 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\pi^-\pi^+\ \text{nonresonant})/\Gamma_{\text{total}}$ Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.8 \times 10^{-5}$	90	BERGFELD	96B	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<3.3 \times 10^{-4}$	90	[135] ADAM	96D	DLPH	$e^+e^- \to Z$
$<4.0 \times 10^{-4}$	90	[136] ABREU	95N	DLPH	Sup. by ADAM 96D
$<3.3 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.9 \times 10^{-4}$	90	[137] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[135] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[136] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[137] AVERY 89B reports $< 1.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^-\pi^+\pi^+\ \text{nonresonant})/\Gamma_{\text{total}}$ Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5.6 \times 10^{-5}$	90	BERGFELD	96B	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{77}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.6 \times 10^{-3}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{78}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.8 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\rho^0)/\Gamma_{\text{total}}$ Γ_{79}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.9 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<1.2 \times 10^{-4}$	90	[138] ADAM	96D	DLPH	$e^+e^- \to Z$
$<1.9 \times 10^{-4}$	90	[139] ABREU	95N	DLPH	Sup. by ADAM 96D
$<1.8 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<8 \times 10^{-5}$	90	[140] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2.6 \times 10^{-4}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[138] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[139] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[140] AVERY 89B reports $< 7 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0\rho^+)/\Gamma_{\text{total}}$ Γ_{80}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.8 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{81}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.1 \times 10^{-3}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\rho^0)/\Gamma_{\text{total}}$ Γ_{82}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9.0 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^+\rho^0)/\Gamma_{\text{total}}$ Γ_{83}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.8 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\rho^0)/\Gamma_{\text{total}}$ Γ_{84}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5 \times 10^{-3}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\overline{K}^0)/\Gamma_{\text{total}}$ Γ_{85}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.1 \times 10^{-5}$	90	GODANG	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+K^-\pi^+\ \text{nonresonant})/\Gamma_{\text{total}}$ Γ_{86}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.5 \times 10^{-5}$	90	BERGFELD	96B	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+K^-K^+)/\Gamma_{\text{total}}$ Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.0 \times 10^{-4}$	90	[141] ADAM	96D	DLPH	$e^+e^- \to Z$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<3.1 \times 10^{-4}$	90	[142] ABREU	95N	DLPH	Sup. by ADAM 96D
$<3.5 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

[141] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[142] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

$\Gamma(K^+\phi)/\Gamma_{\text{total}}$ Γ_{88}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.2 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<2.8 \times 10^{-4}$	90	[143] ADAM	96D	DLPH	$e^+e^- \to Z$
$<4.4 \times 10^{-4}$	90	[144] ABREU	95N	DLPH	Sup. by ADAM 96D
$<1.8 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<9 \times 10^{-5}$	90	[145] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2.1 \times 10^{-4}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[143] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[144] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[145] AVERY 89B reports $< 8 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^+K^-K^+\ \text{nonresonant})/\Gamma_{\text{total}}$ Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.8 \times 10^{-5}$	90	BERGFELD	96B	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+K^+K^-)/\Gamma_{\text{total}}$ Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.6 \times 10^{-3}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\phi)/\Gamma_{\text{total}}$ Γ_{91}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.0 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<1.3 \times 10^{-3}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^+\phi)/\Gamma_{\text{total}}$ Γ_{92}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.1 \times 10^{-3}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\phi)/\Gamma_{\text{total}}$ Γ_{93}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-3}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+f_0(980))/\Gamma_{\text{total}}$ Γ_{94}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8 \times 10^{-5}$	90	[146] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[146] AVERY 89B reports $< 7 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\gamma)/\Gamma_{\text{total}}$ Γ_{95}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$(5.7 \pm 3.1 \pm 1.1) \times 10^{-5}$		5	[147] AMMAR	93	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$< 5.5 \times 10^{-4}$	90		[148] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$
$< 5.5 \times 10^{-4}$	90		[149] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$< 1.8 \times 10^{-3}$	90		AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[147] AMMAR 93 observed 4.1 ± 2.3 events above background.

[148] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

[149] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K_1(1270)^+\gamma)/\Gamma_{\text{total}}$ Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0073	90	[150] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[150] ALBRECHT 89G reports < 0.0066 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^+\gamma)/\Gamma_{\text{total}}$ Γ_{97}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	[151] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[151] ALBRECHT 89G reports < 0.0020 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_2^*(1430)^+\gamma)/\Gamma_{\text{total}}$ Γ_{98}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0014	90	[152] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[152] ALBRECHT 89G reports < 0.0013 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(1680)^+\gamma)/\Gamma_{\text{total}}$ Γ_{99}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0019	90	[153] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[153] ALBRECHT 89G reports < 0.0017 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_3^*(1780)^+\gamma)/\Gamma_{\text{total}}$ — Γ_{100}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0055	90	[154] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[154] ALBRECHT 89G reports < 0.005 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_4^*(2045)^+\gamma)/\Gamma_{\text{total}}$ — Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0099	90	[155] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[155] ALBRECHT 89G reports < 0.0090 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{102}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.0 \times 10^{-5}$	90	GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.7 \times 10^{-5}$	90	ASNER 96	CLE2	Repl. by GODANG 98
$<2.4 \times 10^{-4}$	90	[156] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<2.3 \times 10^{-3}$	90	[157] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[156] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[157] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{103}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-4}$	90	[158] ADAM 96D	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.2 \times 10^{-4}$	90	[159] ABREU 95N	DLPH	Sup. by ADAM 96D
$<4.5 \times 10^{-4}$	90	[160] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.9 \times 10^{-4}$	90	[161] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[158] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[159] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[160] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[161] BORTOLETTO 89 reports $< 1.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\rho^0\pi^+)/\Gamma_{\text{total}}$ — Γ_{104}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<4.3 \times 10^{-5}$	90		ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.6 \times 10^{-4}$	90		[162] ADAM 96D	DLPH	$e^+e^- \to Z$
$<2.6 \times 10^{-4}$	90		[163] ABREU 95N	DLPH	Sup. by ADAM 96D
$<1.5 \times 10^{-4}$	90		[164] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.7 \times 10^{-4}$	90		[165] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2.3 \times 10^{-4}$	90		[165] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<6 \times 10^{-4}$	90	0	GILES 84	CLEO	Repl. by BEBEK 87

[162] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[163] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[164] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[165] Papers assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$[\Gamma(K^*(892)^0\pi^+) + \Gamma(\rho^0\pi^+)]/\Gamma_{\text{total}}$ — $(\Gamma_{73}+\Gamma_{104})/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$(17\ ^{+12}_{-8} \pm 2) \times 10^{-5}$	[166] ADAM 96D	DLPH	$e^+e^- \to Z$

[166] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

$\Gamma(\pi^+ f_0(980))/\Gamma_{\text{total}}$ — Γ_{105}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-4}$	90	[167] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[167] BORTOLETTO 89 reports $< 1.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+ f_2(1270))/\Gamma_{\text{total}}$ — Γ_{106}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.4 \times 10^{-4}$	90	[168] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[168] BORTOLETTO 89 reports $< 2.1 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^-\pi^+ \text{ nonresonant})/\Gamma_{\text{total}}$ — Γ_{107}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.1 \times 10^{-5}$	90	BERGFELD 96B	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_{108}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.9 \times 10^{-4}$	90	[169] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[169] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{109}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.7 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.5 \times 10^{-4}$	90	[170] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[170] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^-\pi^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{110}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.0 \times 10^{-3}$	90	[171] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[171] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\rho^0)/\Gamma_{\text{total}}$ — Γ_{111}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[172] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[172] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{112}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7 \times 10^{-3}$	90	[173] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[173] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\pi^+)/\Gamma_{\text{total}}$ — Γ_{113}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.0 \times 10^{-4}$	90	[174] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[174] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\omega\pi^+)/\Gamma_{\text{total}}$ — Γ_{114}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.0 \times 10^{-4}$	90	[175] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[175] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta\pi^+)/\Gamma_{\text{total}}$ — Γ_{115}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.5 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<7.0 \times 10^{-4}$	90	[176] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[176] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta'\pi^+)/\Gamma_{\text{total}}$ — Γ_{116}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.1 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta'\rho^+)/\Gamma_{\text{total}}$ — Γ_{117}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.7 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta\rho^+)/\Gamma_{\text{total}}$ — Γ_{118}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.2 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ — Γ_{119}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.6 \times 10^{-4}$	90	[177] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[177] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_1(1260)^+)/\Gamma_{\text{total}}$ — Γ_{120}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.2 \times 10^{-4}$	90	[178] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.0 \times 10^{-4}$	90	[179] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<3.2 \times 10^{-3}$	90	[178] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[178] BORTOLETTO 89 reports $< 5.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[179] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_2(1320)^+)/\Gamma_{\text{total}}$ — Γ_{121}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.2 \times 10^{-4}$	90	[180] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6 \times 10^{-3}$	90	[181] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[180] BORTOLETTO 89 reports $< 6.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[181] BEBEK 87reports $< 2.3 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{122}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.3 \times 10^{-3}$	90	[182] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[182] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+ a_1(1260)^0)/\Gamma_{\rm total}$ — Γ_{123}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.3\times10^{-2}$	90	[183] ALBRECHT 90B	ARG	$e^+e^-\to\Upsilon(4S)$

[183] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p}\pi^+)/\Gamma_{\rm total}$ — Γ_{124}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.6\times10^{-4}$	90	[184] BEBEK 89	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.0\times10^{-4}$	90	[185] ABREU 95N	DLPH	Sup. by ADAM 96D
$(5.7\pm1.5\pm2.1)\times10^{-4}$		[186] ALBRECHT 88F	ARG	$e^+e^-\to\Upsilon(4S)$

[184] BEBEK 89 reports $<1.4\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[185] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[186] ALBRECHT 88F reports $(5.2\pm1.4\pm1.9)\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{p}\pi^+\ \text{nonresonant})/\Gamma_{\rm total}$ — Γ_{125}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<5.3\times10^{-5}$	90	BERGFELD 96B	CLE2	$e^+e^-\to\Upsilon(4S)$

$\Gamma(p\overline{p}\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{126}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<5.2\times10^{-4}$	90	[187] ALBRECHT 88F	ARG	$e^+e^-\to\Upsilon(4S)$

[187] ALBRECHT 88F reports $<4.7\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{p}K^+\ \text{nonresonant})/\Gamma_{\rm total}$ — Γ_{127}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<8.9\times10^{-5}$	90	BERGFELD 96B	CLE2	$e^+e^-\to\Upsilon(4S)$

$\Gamma(p\overline{\Lambda})/\Gamma_{\rm total}$ — Γ_{128}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<6\times10^{-5}$	90	[188] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9.3\times10^{-5}$	90	[189] ALBRECHT 88F	ARG	$e^+e^-\to\Upsilon(4S)$

[188] AVERY 89B reports $<5\times10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[189] ALBRECHT 88F reports $<8.5\times10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{\Lambda}\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{129}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<2.0\times10^{-4}$	90	[190] ALBRECHT 88F	ARG	$e^+e^-\to\Upsilon(4S)$

[190] ALBRECHT 88F reports $<1.8\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\overline{\Delta}^0 p)/\Gamma_{\rm total}$ — Γ_{130}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<3.8\times10^{-4}$	90	[191] BORTOLETTO89	CLEO	$e^+e^-\to\Upsilon(4S)$

[191] BORTOLETTO 89 reports $<3.3\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^{++}\overline{p})/\Gamma_{\rm total}$ — Γ_{131}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.5\times10^{-4}$	90	[192] BORTOLETTO89	CLEO	$e^+e^-\to\Upsilon(4S)$

[192] BORTOLETTO 89 reports $<1.3\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Lambda_c^- p\pi^+)/\Gamma_{\rm total}$ — Γ_{132}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
$6.2^{+2.3}_{-2.0}\pm1.6$	[193] FU 97	CLE2	$e^+e^-\to\Upsilon(4S)$

[193] FU 97 uses PDG 96 values of Λ_c branching fraction.

$\Gamma(\Lambda_c^- p\pi^+\pi^0)/\Gamma_{\rm total}$ — Γ_{133}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<3.12\times10^{-3}$	90	[194] FU 97	CLE2	$e^+e^-\to\Upsilon(4S)$

[194] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\Lambda_c^- p\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{134}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.46\times10^{-3}$	90	[195] FU 97	CLE2	$e^+e^-\to\Upsilon(4S)$

[195] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\Lambda_c^- p\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ — Γ_{135}/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.34\times10^{-2}$	90	[196] FU 97	CLE2	$e^+e^-\to\Upsilon(4S)$

[196] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\pi^+e^+e^-)/\Gamma_{\rm total}$ — Γ_{136}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0039	90	[197] WEIR 90B	MRK2	e^+e^- 29 GeV

[197] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_{137}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0091	90	[198] WEIR 90B	MRK2	e^+e^- 29 GeV

[198] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+e^+e^-)/\Gamma_{\rm total}$ — Γ_{138}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<6\times10^{-5}$	90	[199] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9.9\times10^{-5}$	90	[200] ALBRECHT 91E	ARG	$e^+e^-\to\Upsilon(4S)$
$<6.8\times10^{-3}$	90	[201] WEIR 90B	MRK2	e^+e^- 29 GeV
$<2.5\times10^{-4}$	90	[202] AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[199] AVERY 89B reports $<5\times10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[200] ALBRECHT 91E reports $<9.0\times10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

[201] WEIR 90B assumes B^+ production cross section from LUND.

[202] AVERY 87 reports $<2.1\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_{139}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.0\times10^{-5}$	90	[203] ABE 96L	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.4\times10^{-4}$	90	[204] ALBRECHT 91E	ARG	$e^+e^-\to\Upsilon(4S)$
$<6.4\times10^{-3}$	90	[205] WEIR 90B	MRK2	e^+e^- 29 GeV
$<1.7\times10^{-4}$	90	[206] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
$<3.8\times10^{-4}$	90	[207] AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[203] ABE 96L measured relative to $B^0\to J/\psi(1S)K^+$ using PDG 94 branching ratios.

[204] ALBRECHT 91E reports $<2.2\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

[205] WEIR 90B assumes B^+ production cross section from LUND.

[206] AVERY 89B reports $<1.5\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[207] AVERY 87 reports $<3.2\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+e^+e^-)/\Gamma_{\rm total}$ — Γ_{140}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<6.9\times10^{-4}$	90	[208] ALBRECHT 91E	ARG	$e^+e^-\to\Upsilon(4S)$

[208] ALBRECHT 91E reports $<6.3\times10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_{141}/Γ

Test for $\Delta B=1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1.2\times10^{-3}$	90	[209] ALBRECHT 91E	ARG	$e^+e^-\to\Upsilon(4S)$

[209] ALBRECHT 91E reports $<1.1\times10^{-3}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+e^+\mu^-)/\Gamma_{\rm total}$ — Γ_{142}/Γ

Test of lepton family number conservation.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0064	90	[210] WEIR 90B	MRK2	e^+e^- 29 GeV

[210] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+e^-\mu^+)/\Gamma_{\rm total}$ — Γ_{143}/Γ

Test of lepton family number conservation.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0064	90	[211] WEIR 90B	MRK2	e^+e^- 29 GeV

[211] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+e^+\mu^-)/\Gamma_{\rm total}$ — Γ_{144}/Γ

Test of lepton family number conservation.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0064	90	[212] WEIR 90B	MRK2	e^+e^- 29 GeV

[212] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+e^-\mu^+)/\Gamma_{\rm total}$ — Γ_{145}/Γ

Test of lepton family number conservation.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.0064	90	[213] WEIR 90B	MRK2	e^+e^- 29 GeV

[213] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+ e^+)/\Gamma_{\text{total}}$ Γ_{146}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0039	90	[214] WEIR	90B	MRK2	e^+e^- 29 GeV

[214] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{147}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0091	90	[215] WEIR	90B	MRK2	e^+e^- 29 GeV

[215] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{148}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0064	90	[216] WEIR	90B	MRK2	e^+e^- 29 GeV

[216] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+ e^+)/\Gamma_{\text{total}}$ Γ_{149}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0039	90	[217] WEIR	90B	MRK2	e^+e^- 29 GeV

[217] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- \mu^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{150}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0091	90	[218] WEIR	90B	MRK2	e^+e^- 29 GeV

[218] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+ \mu^+)/\Gamma_{\text{total}}$ Γ_{151}/Γ

Test of total lepton number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.0064	90	[219] WEIR	90B	MRK2	e^+e^- 29 GeV

[219] WEIR 90B assumes B^+ production cross section from LUND.

$B^{\pm}$ REFERENCES

ABE	98B	PR D57 5382	F. Abe+	(CDF Collab.)
BEHRENS	98	PRL 80 3710	B.H. Behrens+	(CLEO Collab.)
BRANDENB...	98	PRL 80 2762	G. Brandenbrug+	(CLEO Collab.)
GODANG	98	PRL 80 3456	R. Godang+	(CLEO Collab.)
ABE	97J	PRL 79 590	+Abe, Akagi, Allen+	(SLD Collab.)
ACCIARRI	97F	PL B396 327	M. Acciarri+	(L3 Collab.)
ARTUSO	97	PL B399 321	M. Artuso+	(CLEO Collab.)
ATHANAS	97	PRL 79 2208	M. Athanas+	(CLEO Collab.)
BROWDER	97	PR D56 11	T. Browder+	(CLEO Collab.)
FU	97	PRL 79 3125	X. Fu+	(CLEO Collab.)
JESSOP	97	PRL 79 4533	C.P. Jessop+	(CLEO Collab.)
ABE	96B	PR D53 3496	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABE	96C	PRL 76 4462	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96H	PRL 76 2015	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABE	96L	PRL 76 4675	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96Q	PR D54 6596	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96R	PRL 77 5176	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ADAM	96D	ZPHY C72 207	W. Adam+	(DELPHI Collab.)
ASNER	96	PR D53 1039	+Athanas, Bliss, Brower+	(CLEO Collab.)
BARISH	96B	PRL 76 1570	+Chadha, Chan, Eigen+	(CLEO Collab.)
BERGFELD	96B	PRL 77 4503	+Eisenstein, Ernst, Gladding+	(CLEO Collab.)
BISHAI	96	PL B369 186	+Fast, Gerndt, Hinson+	(CLEO Collab.)
BUSKULIC	96J	ZPHY C71 31	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
GIBAUT	96	PR D53 4734	+Kinoshita, Pomianowski, Barish+	(CLEO Collab.)
PDG	96	PR D54 1		
ABREU	95N	PL B357 255	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95Q	ZPHY C68 13	+Adam, Adye, Agasi+	(DELPHI Collab.)
ADAM	95	ZPHY C68 363	+Adye, Agasi, Ajinenko+	(DELPHI Collab.)
AKERS	95T	ZPHY C67 379	+Alexander, Allison, Ametewee+	(OPAL Collab.)
ALBRECHT	95D	PL B353 554	+Hamacher, Hofmann, Kirchoff+	(ARGUS Collab.)
ALEXANDER	95	PL B341 435	+Bebek, Berkelman, Bloom+	(CLEO Collab.)
Also	95C	PL B347 469 (erratum)	Alexander, Bebek, Berkelman, Bloom+	(CLEO Collab.)
ARTUSO	95	PRL 75 785	+Gao, Goldberg, He+	(CLEO Collab.)
BARISH	95	PR D51 1014	+Chadha, Chan, Cowen+	(CLEO Collab.)
BUSKULIC	95	PL B343 444	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
ABE	94D	PRL 72 3456	+Albrow, Amidei, Anway-Wiese, Apollinari	(CDF Collab.)
ALAM	94	PR D50 43	+Kim, Nemati, O'Neill, Severini+	(CLEO Collab.)
ALBRECHT	94D	PL B335 526	+Hamacher, Hofmann, Kirchhoff, Mankel+	(ARGUS Collab.)
ATHANAS	94	PRL 73 3503	+Brower, Masek, Paar, Gronberg+	(CLEO Collab.)
Also	95	PRL 74 3090 (erratum)	Athanas, Brower, Masek, Paar+	(CLEO Collab.)
PDG	94	PR D50 1173	Montanet+	(CERN, LBL, BOST, IFIC+)
STONE	94	HEPSY 93-11		
ABREU	93D	ZPHY C57 181	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	93G	PL B312 253	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACTON	93C	PL B307 247	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALBRECHT	93E	ZPHY C60 11	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALEXANDER	93B	PL B319 365	+Bebek, Berkelman, Bloom, Browder+	(CLEO Collab.)
AMMAR	93	PRL 71 674	+Ball, Baringer, Coppage, Copty+	(CLEO Collab.)
BEAN	93B	PRL 70 2681	+Gronberg, Kutschke, Menary, Morrison+	(CLEO Collab.)
BUSKULIC	93D	PL B307 194	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
Also	94H	PL B325 537 (errata)		
SANGHERA	93	PR D47 791	+Skwarnicki, Stroynowski, Artuso, Goldberg+	(CLEO Collab.)
ALBRECHT	92C	PL B275 195	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92E	PL B277 209	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92G	ZPHY C54 1	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
BORTOLETTO	92	PR D45 21	+Brown, Dominick, McIlwain+	(CLEO Collab.)
BUSKULIC	92G	PL B295 396	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
ALBRECHT	91B	PL B254 288	+Glaeser, Harder, Krueger, Nippe+	(ARGUS Collab.)
ALBRECHT	91C	PL B255 297	+Ehrlichmann, Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	91E	PL B262 148	+Glaeser, Harder, Krueger, Nippe+	(ARGUS Collab.)
BERKELMAN	91	ARNPS 41 1	+Stone	(CORN, SYRA)
"Decays of *B* Mesons"				
FULTON	91	PR D43 651	+Jensen, Johnson, Kagan, Kass+	(CLEO Collab.)
ALBRECHT	90B	PL B241 278	+Glaeser, Harder, Krueger, Nilsson+	(ARGUS Collab.)
ALBRECHT	90J	ZPHY C48 543	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ANTREASYAN	90B	ZPHY C48 553	+Bartels, Bieler, Bienlein, Bizzeti+	(Crystal Ball Collab.)
BORTOLETTO	90	PRL 64 2117	+Goldberg, Horwitz, Jain, Mestayer+	(CLEO Collab.)
Also	92	PR D45 21	Bortoletto, Brown, Dominick, McIlwain+	(CLEO Collab.)
WEIR	90B	PR D41 1384	+Klein, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
ALBRECHT	89G	PL B229 304	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
AVERY	89B	PL B223 470	+Besson, Garren, Yelton+	(CLEO Collab.)
BEBEK	89	PRL 62 8	+Berkelman, Blucher+	(CLEO Collab.)
BORTOLETTO	89	PRL 62 2436	+Goldberg, Horwitz, Mestayer+	(CLEO Collab.)
ALBRECHT	88F	PL B209 119	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88K	PL B215 424	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	87C	PL B185 218	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
AVERY	87	PL B183 429	+Besson, Bowcock, Giles+	(CLEO Collab.)
BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
ALAM	86	PR D34 3279	+Katayama, Kim, Sun+	(CLEO Collab.)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
GILES	84	PR D30 2279	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)

B^0

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

See also the $B^{\pm}/B^0$ ADMIXTURE and $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE sections.

See the Notes "Experimental Highlights of *B* Meson Production and Decay" and "Semileptonic Decays of *B* Mesons" at the beginning of the $B^{\pm}$ Particle Listings and the Note on "B^0-$\overline{B}^0$ Mixing and *CP* Violation in *B* Decay" near the end of the B^0 Particle Listings.

B^0 MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $(m_{B^0_s} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences. m_{B^0} data are excluded from the fit because they are not independent.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5279.2±1.8 OUR FIT					
5279.8±1.6 OUR AVERAGE					
5281.3±2.2 ±1.4	51	[1] ABE	96B	CDF	$p\overline{p}$ at 1.8 TeV
5279.2±0.54±2.0	340	[2] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
5278.0±0.4 ±2.0		[2] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
5279.6±0.7 ±2.0	40	[2,3] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
5280.6±0.8 ±2.0		[2] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5278.2±1.0 ±3.0	40	ALBRECHT	87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
5279.5±1.6 ±3.0	7	[4] ALBRECHT	87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[1] Excluded from fit because it is not independent of ABE 96B B^0_s mass and B^0_s-B mass difference.

[2] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average. See "Treatment of Errors" section of the Introductory Text. These experiments actually measure the difference between half of E_{cm} and the B mass.

[3] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.

[4] Found using fully reconstructed decays with J/ψ. ALBRECHT 87D assume $m_{\Upsilon(4S)}$ = 10577 MeV.

$m_{B^0} - m_{B^+}$

The mass difference measurements are not independent of the $B^{\pm}$ and B^0 mass measurement by the same experimenters. The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $(m_{B^0_s} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.35±0.29 OUR FIT Error includes scale factor of 1.1.				
0.34±0.32 OUR AVERAGE Error includes scale factor of 1.2.				
0.41±0.25±0.19	ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
−0.4 ±0.6 ±0.5	BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
−0.9 ±1.2 ±0.5	ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
2.0 ±1.1 ±0.3	[5] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[5] BEBEK 87 actually measure the difference between half of E_{cm} and the $B^{\pm}$ or B^0 mass, so the $m_{B^0} - m_{B^{\pm}}$ is more accurate. Assume $m_{\Upsilon(4S)}$ = 10580 MeV.

$m_{B^0_H} - m_{B^0_L}$

See the B^0-$\overline{B}^0$ MIXING PARAMETERS section near the end of these B^0 Listings.

B^0 MEAN LIFE

See $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE section for data on B-hadron mean life averaged over species of bottom particles.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.56 ±0.04 OUR EVALUATION					
1.58 ±0.09 ±0.02		[6] ABE	98B	CDF	$p\overline{p}$ at 1.8 TeV
1.64 ±0.08 ±0.08		[7] ABE	97J	SLD	$e^+e^- \rightarrow Z$
1.532±0.041±0.040		[8] ABREU	97F	DLPH	$e^+e^- \rightarrow Z$
1.54 ±0.08 ±0.06		[9] ABE	96C	CDF	$p\overline{p}$ at 1.8 TeV
1.61 ±0.07 ±0.04		[9] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.25\ ^{+0.15}_{-0.13}\ \pm0.05$	121	[6] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.49\ ^{+0.17}_{-0.15}\ ^{+0.08}_{-0.06}$		[10] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.61\ ^{+0.14}_{-0.13}\ \pm0.08$		[9,11] ABREU	95Q	DLPH	$e^+e^- \rightarrow Z$
1.63 ±0.14 ±0.13		[12] ADAM	95	DLPH	$e^+e^- \rightarrow Z$
1.53 ±0.12 ±0.08		[9,13] AKERS	95T	OPAL	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.55 ±0.06 ±0.03		[14] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
1.62 ±0.12		[15] ADAM	95	DLPH	$e^+e^- \rightarrow Z$
1.57 ±0.18 ±0.08	121	[6] ABE	94D	CDF	Repl. by ABE 98B
$1.17\ ^{+0.29}_{-0.23}\ \pm0.16$	96	[9] ABREU	93D	DLPH	Sup. by ABREU 95Q
1.55 ±0.25 ±0.18	76	[12] ABREU	93G	DLPH	Sup. by ADAM 95
$1.51\ ^{+0.24}_{-0.23}\ ^{+0.12}_{-0.14}$	78	[9] ACTON	93C	OPAL	Sup. by AKERS 95T
$1.52\ ^{+0.20}_{-0.18}\ ^{+0.07}_{-0.13}$	77	[9] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96J
$1.20\ ^{+0.52}_{-0.36}\ ^{+0.16}_{-0.14}$	15	[16] WAGNER	90	MRK2	E^{ee}_{cm}= 29 GeV
$0.82\ ^{+0.57}_{-0.37}\ \pm0.27$		[17] AVERILL	89	HRS	E^{ee}_{cm}= 29 GeV

[6] Measured mean life using fully reconstructed decays.

[7] Data analyzed using charge of secondary vertex.

[8] Data analyzed using inclusive $D/D^* \ell X$.

[9] Data analyzed using $D/D^* \ell X$ event vertices.

[10] Measured mean life using partially reconstructed $D^{*-}\pi^+ X$ vertices.

[11] ABREU 95Q assumes $B(B^0 \rightarrow D^{**-}\ell^+\nu_\ell) = 3.2 \pm 1.7\%$.

[12] Data analyzed using vertex-charge technique to tag B charge.

[13] AKERS 95T assumes $B(B^0 \rightarrow D_s^{(*)} D^{0(*)}) = 5.0 \pm 0.9\%$ to find B^+/B^0 yield.

[14] Combined result of $D/D^* \ell x$ analysis, fully reconstructed B analysis, and partially reconstruced $D^{*-}\pi^+ X$ analysis.

[15] Combined ABREU 95Q and ADAM 95 result.

[16] WAGNER 90 tagged B^0 mesons by their decays into $D^{*-}e^+\nu$ and $D^{*-}\mu^+\nu$ where the D^{*-} is tagged by its decay into $\pi^-\overline{D}^0$.

[17] AVERILL 89 is an estimate of the B^0 mean lifetime assuming that $B^0 \rightarrow D^{*+} + X$ always.

MEAN LIFE RATIO τ_{B^+}/τ_{B^0}

τ_{B^+}/τ_{B^0} (average of direct and inferred)

VALUE	DOCUMENT ID
1.02±0.04 OUR AVERAGE Includes data from the 2 datablocks that follow this one.	

τ_{B^+}/τ_{B^0} (direct measurements)

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1.04±0.04 OUR EVALUATION					
1.06±0.07±0.02		[18] ABE	98B	CDF	$p\overline{p}$ at 1.8 TeV
1.01±0.07±0.06		[19] ABE	97J	SLD	$e^+e^- \rightarrow Z$
1.01±0.11±0.02		[20] ABE	96C	CDF	$p\overline{p}$ at 1.8 TeV
0.98±0.08±0.03		[20] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.27^{+0.23}_{-0.19}{}^{+0.03}_{-0.02}$		[18] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
$1.00^{+0.17}_{-0.15}\pm0.10$		[20,21] ABREU	95Q	DLPH	$e^+e^- \rightarrow Z$
$1.06^{+0.13}_{-0.10}\pm0.10$		[22] ADAM	95	DLPH	$e^+e^- \rightarrow Z$
$0.99\pm0.14^{+0.05}_{-0.04}$		[20,23] AKERS	95T	OPAL	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.03±0.08±0.02		[24] BUSKULIC	96J	ALEP	$e^+e^- \rightarrow Z$
1.02±0.16±0.05	269	[18] ABE	94D	CDF	Repl. by ABE 98B
$1.11^{+0.51}_{-0.39}\pm0.11$	188	[20] ABREU	93D	DLPH	Sup. by ABREU 95Q
$1.01^{+0.29}_{-0.22}\pm0.12$	253	[22] ABREU	93G	DLPH	Sup. by ADAM 95
$1.0\ ^{+0.33}_{-0.25}\pm0.08$	130	ACTON	93C	OPAL	Sup. by AKERS 95T
$0.96^{+0.19}_{-0.15}{}^{+0.18}_{-0.12}$	154	[20] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96J

[18] Measured using fully reconstructed decays.

[19] Data analyzed using charge of secondary vertex.

[20] Data analyzed using $D/D^* \ell X$ vertices.

[21] ABREU 95Q assumes $B(B^0 \rightarrow D^{**-}\ell^+\nu_\ell) = 3.2 \pm 1.7\%$.

[22] Data analyzed using vertex-charge technique to tag B charge.

[23] AKERS 95T assumes $B(B^0 \rightarrow D_s^{(*)} D^{0(*)}) = 5.0 \pm 0.9\%$ to find B^+/B^0 yield.

[24] Combined result of $D/D^* \ell X$ analysis and fully reconstructed B analysis.

τ_{B^+}/τ_{B^0} (inferred from branching fractions)

These measurements are inferred from the branching fractions for semileptonic decay or other spectator-dominated decays by assuming that the rates for such decays are equal for B^0 and B^+. We do not use measurements which assume equal production of B^0 and B^+ because of the large uncertainty in the production ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.						
$\mathbf{0.95^{+0.117}_{-0.080}\pm0.091}$			[25] ARTUSO	97	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15±0.17 ±0.06			[26] JESSOP	97	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.93±0.18 ±0.12			[27] ATHANAS	94	CLE2	Sup. by ARTUSO 97
0.91±0.27 ±0.21			[28] ALBRECHT	92C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
1.0 ±0.4		29	[28,29] ALBRECHT	92G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.89±0.19 ±0.13			[28] FULTON	91	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
1.00±0.23 ±0.14			[28] ALBRECHT	89L	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.49 to 2.3	90		[30] BEAN	87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[25] ARTUSO 97 uses partial reconstruction of $B \rightarrow D^* \ell \nu_\ell$ and independent of B^0 and B^+ production fraction.

[26] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[27] ATHANAS 94 uses events tagged by fully reconstructed B^- decays and partially or fully reconstructed B^0 decays.

[28] Assumes equal production of B^0 and B^+.

[29] ALBRECHT 92G data analyzed using $B \rightarrow D_s\overline{D}, D_s\overline{D}^*, D_s^*\overline{D}, D_s^*\overline{D}^*$ events.

[30] BEAN 87B assume the fraction of $B^0\overline{B}^0$ events at the $\Upsilon(4S)$ is 0.41.

B^0 DECAY MODES

$\overline{B}^0$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the B are listed in the $B^{\pm}/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\ell^+\nu_\ell$ anything	[a]	(10.5 ± 0.8) %	
Γ_2	$D^-\ell^+\nu_\ell$	[a]	(2.00 ± 0.25) %	
Γ_3	$D^*(2010)^-\ell^+\nu_\ell$	[a]	(4.60 ± 0.27) %	
Γ_4	$\rho^-\ell^+\nu_\ell$	[a]	$(2.5\ ^{+0.8}_{-1.0}) \times 10^{-4}$	
Γ_5	$\pi^-\ell^+\nu_\ell$		$(1.8 \pm 0.6) \times 10^{-4}$	
	Inclusive modes			
Γ_6	$\pi^-\mu^+\nu_\mu$			
Γ_7	K^+ anything		(78 ± 80) %	
	D*, *D*, **or** ***D*****s* modes**			
Γ_8	$D^-\pi^+$		$(3.0 \pm 0.4) \times 10^{-3}$	
Γ_9	$D^-\rho^+$		$(7.9 \pm 1.4) \times 10^{-3}$	
Γ_{10}	$\overline{D}^0\pi^+\pi^-$		$< 1.6 \times 10^{-3}$	CL=90%
Γ_{11}	$D^*(2010)^-\pi^+$		$(2.76 \pm 0.21) \times 10^{-3}$	
Γ_{12}	$D^-\pi^+\pi^+\pi^-$		$(8.0 \pm 2.5) \times 10^{-3}$	
Γ_{13}	$(D^-\pi^+\pi^+\pi^-)$ nonresonant		$(3.9 \pm 1.9) \times 10^{-3}$	
Γ_{14}	$D^-\pi^+\rho^0$		$(1.1 \pm 1.0) \times 10^{-3}$	
Γ_{15}	$D^-a_1(1260)^+$		$(6.0 \pm 3.3) \times 10^{-3}$	
Γ_{16}	$D^*(2010)^-\pi^+\pi^0$		(1.5 ± 0.5) %	
Γ_{17}	$D^*(2010)^-\rho^+$		$(6.7 \pm 3.3) \times 10^{-3}$	
Γ_{18}	$D^*(2010)^-\pi^+\pi^+\pi^-$		$(7.6 \pm 1.7) \times 10^{-3}$	S=1.3
Γ_{19}	$(D^*(2010)^-\pi^+\pi^+\pi^-)$ nonresonant		$(0.0 \pm 2.5) \times 10^{-3}$	
Γ_{20}	$D^*(2010)^-\pi^+\rho^0$		$(5.7 \pm 3.1) \times 10^{-3}$	
Γ_{21}	$D^*(2010)^-a_1(1260)^+$		(1.30 ± 0.27) %	
Γ_{22}	$D^*(2010)^-\pi^+\pi^+\pi^-\pi^0$		(3.4 ± 1.8) %	
Γ_{23}	$\overline{D}_2^*(2460)^-\pi^+$		$< 2.2 \times 10^{-3}$	CL=90%
Γ_{24}	$\overline{D}_2^*(2460)^-\rho^+$		$< 4.9 \times 10^{-3}$	CL=90%

Γ_{25}	$D^- D_s^+$		(8.0 ± 3.0)	$\times 10^{-3}$	
Γ_{26}	$D^*(2010)^- D_s^+$		(9.6 ± 3.4)	$\times 10^{-3}$	
Γ_{27}	$D^- D_s^{*+}$		(1.0 ± 0.5)	%	
Γ_{28}	$D^*(2010)^- D_s^{*+}$		(2.0 ± 0.7)	%	
Γ_{29}	$D_s^+ \pi^-$		< 2.8	$\times 10^{-4}$	CL=90%
Γ_{30}	$D_s^{*+} \pi^-$		< 5	$\times 10^{-4}$	CL=90%
Γ_{31}	$D_s^+ \rho^-$		< 7	$\times 10^{-4}$	CL=90%
Γ_{32}	$D_s^{*+} \rho^-$		< 8	$\times 10^{-4}$	CL=90%
Γ_{33}	$D_s^+ a_1(1260)^-$		< 2.6	$\times 10^{-3}$	CL=90%
Γ_{34}	$D_s^{*+} a_1(1260)^-$		< 2.2	$\times 10^{-3}$	CL=90%
Γ_{35}	$D_s^- K^+$		< 2.4	$\times 10^{-4}$	CL=90%
Γ_{36}	$D_s^{*-} K^+$		< 1.7	$\times 10^{-4}$	CL=90%
Γ_{37}	$D_s^- K^*(892)^+$		< 9.9	$\times 10^{-4}$	CL=90%
Γ_{38}	$D_s^{*-} K^*(892)^+$		< 1.1	$\times 10^{-3}$	CL=90%
Γ_{39}	$D_s^- \pi^+ K^0$		< 5	$\times 10^{-3}$	CL=90%
Γ_{40}	$D_s^{*-} \pi^+ K^0$		< 3.1	$\times 10^{-3}$	CL=90%
Γ_{41}	$D_s^- \pi^+ K^*(892)^0$		< 4	$\times 10^{-3}$	CL=90%
Γ_{42}	$D_s^{*-} \pi^+ K^*(892)^0$		< 2.0	$\times 10^{-3}$	CL=90%
Γ_{43}	$\overline{D}^0 \pi^0$		< 1.2	$\times 10^{-4}$	CL=90%
Γ_{44}	$\overline{D}^0 \rho^0$		< 3.9	$\times 10^{-4}$	CL=90%
Γ_{45}	$\overline{D}^0 \eta$		< 1.3	$\times 10^{-4}$	CL=90%
Γ_{46}	$\overline{D}^0 \eta'$		< 9.4	$\times 10^{-4}$	CL=90%
Γ_{47}	$\overline{D}^0 \omega$		< 5.1	$\times 10^{-4}$	CL=90%
Γ_{48}	$\overline{D}^*(2007)^0 \pi^0$		< 4.4	$\times 10^{-4}$	CL=90%
Γ_{49}	$\overline{D}^*(2007)^0 \rho^0$		< 5.6	$\times 10^{-4}$	CL=90%
Γ_{50}	$\overline{D}^*(2007)^0 \eta$		< 2.6	$\times 10^{-4}$	CL=90%
Γ_{51}	$\overline{D}^*(2007)^0 \eta'$		< 1.4	$\times 10^{-3}$	CL=90%
Γ_{52}	$\overline{D}^*(2007)^0 \omega$		< 7.4	$\times 10^{-4}$	CL=90%
Γ_{53}	$D^*(2010)^+ D^*(2010)^-$		< 2.2	$\times 10^{-3}$	CL=90%
Γ_{54}	$D^*(2010)^+ D^-$		< 1.8	$\times 10^{-3}$	CL=90%
Γ_{55}	$D^+ D^*(2010)^-$		< 1.2	$\times 10^{-3}$	CL=90%

Charmonium modes

Γ_{56}	$J/\psi(1S) K^0$		(8.9 ± 1.2)	$\times 10^{-4}$	
Γ_{57}	$J/\psi(1S) K^+ \pi^-$		(1.1 ± 0.6)	$\times 10^{-3}$	
Γ_{58}	$J/\psi(1S) K^*(892)^0$		(1.35 ± 0.18)	$\times 10^{-3}$	
Γ_{59}	$J/\psi(1S) \pi^0$		< 5.8	$\times 10^{-5}$	CL=90%
Γ_{60}	$J/\psi(1S) \eta$		< 1.2	$\times 10^{-3}$	CL=90%
Γ_{61}	$J/\psi(1S) \rho^0$		< 2.5	$\times 10^{-4}$	CL=90%
Γ_{62}	$J/\psi(1S) \omega$		< 2.7	$\times 10^{-4}$	CL=90%
Γ_{63}	$\psi(2S) K^0$		< 8	$\times 10^{-4}$	CL=90%
Γ_{64}	$\psi(2S) K^+ \pi^-$		< 1	$\times 10^{-3}$	CL=90%
Γ_{65}	$\psi(2S) K^*(892)^0$		(1.4 ± 0.9)	$\times 10^{-3}$	
Γ_{66}	$\chi_{c1}(1P) K^0$		< 2.7	$\times 10^{-3}$	CL=90%
Γ_{67}	$\chi_{c1}(1P) K^*(892)^0$		< 2.1	$\times 10^{-3}$	CL=90%

K or *K** modes

Γ_{68}	$K^+ \pi^-$		$(1.5 {}^{+0.5}_{-0.4})$	$\times 10^{-5}$	
Γ_{69}	$K^0 \pi^0$		< 4.1	$\times 10^{-5}$	CL=90%
Γ_{70}	$\eta' K^0$		$(4.7 {}^{+2.8}_{-2.2})$	$\times 10^{-5}$	
Γ_{71}	$\eta' K^*(892)^0$		< 3.9	$\times 10^{-5}$	CL=90%
Γ_{72}	$\eta K^*(892)^0$		< 3.0	$\times 10^{-5}$	CL=90%
Γ_{73}	ηK^0		< 3.3	$\times 10^{-5}$	CL=90%
Γ_{74}	$K^+ K^-$		< 4.3	$\times 10^{-6}$	CL=90%
Γ_{75}	$K^0 \overline{K}^0$		< 1.7	$\times 10^{-5}$	CL=90%
Γ_{76}	$K^+ \rho^-$		< 3.5	$\times 10^{-5}$	CL=90%
Γ_{77}	$K^0 \pi^+ \pi^-$				
Γ_{78}	$K^0 \rho^0$		< 3.9	$\times 10^{-5}$	CL=90%
Γ_{79}	$K^0 f_0(980)$		< 3.6	$\times 10^{-4}$	CL=90%
Γ_{80}	$K^*(892)^+ \pi^-$		< 7.2	$\times 10^{-5}$	CL=90%
Γ_{81}	$K^*(892)^0 \pi^0$		< 2.8	$\times 10^{-5}$	CL=90%
Γ_{82}	$K_2^*(1430)^+ \pi^-$		< 2.6	$\times 10^{-3}$	CL=90%
Γ_{83}	$K^0 K^+ K^-$		< 1.3	$\times 10^{-3}$	CL=90%
Γ_{84}	$K^0 \phi$		< 8.8	$\times 10^{-5}$	CL=90%
Γ_{85}	$K^- \pi^+ \pi^+ \pi^-$	[b]	< 2.3	$\times 10^{-4}$	CL=90%
Γ_{86}	$K^*(892)^0 \pi^+ \pi^-$		< 1.4	$\times 10^{-3}$	CL=90%
Γ_{87}	$K^*(892)^0 \rho^0$		< 4.6	$\times 10^{-4}$	CL=90%
Γ_{88}	$K^*(892)^0 f_0(980)$		< 1.7	$\times 10^{-4}$	CL=90%
Γ_{89}	$K_1(1400)^+ \pi^-$		< 1.1	$\times 10^{-3}$	CL=90%
Γ_{90}	$K^- a_1(1260)^+$	[b]	< 2.3	$\times 10^{-4}$	CL=90%
Γ_{91}	$K^*(892)^0 K^+ K^-$		< 6.1	$\times 10^{-4}$	CL=90%
Γ_{92}	$K^*(892)^0 \phi$		< 4.3	$\times 10^{-5}$	CL=90%
Γ_{93}	$K_1(1400)^0 \rho^0$		< 3.0	$\times 10^{-3}$	CL=90%
Γ_{94}	$K_1(1400)^0 \phi$		< 5.0	$\times 10^{-3}$	CL=90%
Γ_{95}	$K_2^*(1430)^0 \rho^0$		< 1.1	$\times 10^{-3}$	CL=90%
Γ_{96}	$K_2^*(1430)^0 \phi$		< 1.4	$\times 10^{-3}$	CL=90%
Γ_{97}	$K^*(892)^0 \gamma$		(4.0 ± 1.9)	$\times 10^{-5}$	
Γ_{98}	$K_1(1270)^0 \gamma$		< 7.0	$\times 10^{-3}$	CL=90%
Γ_{99}	$K_1(1400)^0 \gamma$		< 4.3	$\times 10^{-3}$	CL=90%
Γ_{100}	$K_2^*(1430)^0 \gamma$		< 4.0	$\times 10^{-4}$	CL=90%
Γ_{101}	$K^*(1680)^0 \gamma$		< 2.0	$\times 10^{-3}$	CL=90%
Γ_{102}	$K_3^*(1780)^0 \gamma$		< 1.0	%	CL=90%
Γ_{103}	$K_4^*(2045)^0 \gamma$		< 4.3	$\times 10^{-3}$	CL=90%
Γ_{104}	$\phi \phi$		< 3.9	$\times 10^{-5}$	CL=90%

Light unflavored meson modes

Γ_{105}	$\pi^+ \pi^-$		< 1.5	$\times 10^{-5}$	CL=90%
Γ_{106}	$\pi^0 \pi^0$		< 9.3	$\times 10^{-6}$	CL=90%
Γ_{107}	$\eta \pi^0$		< 8	$\times 10^{-6}$	CL=90%
Γ_{108}	$\eta \eta$		< 1.8	$\times 10^{-5}$	CL=90%
Γ_{109}	$\eta' \pi^0$		< 1.1	$\times 10^{-5}$	CL=90%
Γ_{110}	$\eta' \eta'$		< 4.7	$\times 10^{-5}$	CL=90%
Γ_{111}	$\eta' \eta$		< 2.7	$\times 10^{-5}$	CL=90%
Γ_{112}	$\eta' \rho^0$		< 2.3	$\times 10^{-5}$	CL=90%
Γ_{113}	$\eta \rho^0$		< 1.3	$\times 10^{-5}$	CL=90%
Γ_{114}	$\pi^+ \pi^- \pi^0$		< 7.2	$\times 10^{-4}$	CL=90%
Γ_{115}	$\rho^0 \pi^0$		< 2.4	$\times 10^{-5}$	CL=90%
Γ_{116}	$\rho^\mp \pi^\pm$	[c]	< 8.8	$\times 10^{-5}$	CL=90%
Γ_{117}	$\pi^+ \pi^- \pi^+ \pi^-$		< 2.3	$\times 10^{-4}$	CL=90%
Γ_{118}	$\rho^0 \rho^0$		< 2.8	$\times 10^{-4}$	CL=90%
Γ_{119}	$a_1(1260)^\mp \pi^\pm$	[c]	< 4.9	$\times 10^{-4}$	CL=90%
Γ_{120}	$a_2(1320)^\mp \pi^\pm$	[c]	< 3.0	$\times 10^{-4}$	CL=90%
Γ_{121}	$\pi^+ \pi^- \pi^0 \pi^0$		< 3.1	$\times 10^{-3}$	CL=90%
Γ_{122}	$\rho^+ \rho^-$		< 2.2	$\times 10^{-3}$	CL=90%
Γ_{123}	$a_1(1260)^0 \pi^0$		< 1.1	$\times 10^{-3}$	CL=90%
Γ_{124}	$\omega \pi^0$		< 4.6	$\times 10^{-4}$	CL=90%
Γ_{125}	$\pi^+ \pi^+ \pi^- \pi^- \pi^0$		< 9.0	$\times 10^{-3}$	CL=90%
Γ_{126}	$a_1(1260)^+ \rho^-$		< 3.4	$\times 10^{-3}$	CL=90%
Γ_{127}	$a_1(1260)^0 \rho^0$		< 2.4	$\times 10^{-3}$	CL=90%
Γ_{128}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$		< 3.0	$\times 10^{-3}$	CL=90%
Γ_{129}	$a_1(1260)^+ a_1(1260)^-$		< 2.8	$\times 10^{-3}$	CL=90%
Γ_{130}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0$		< 1.1	%	CL=90%

Baryon modes

Γ_{131}	$p \overline{p}$		< 1.8	$\times 10^{-5}$	CL=90%
Γ_{132}	$p \overline{p} \pi^+ \pi^-$		< 2.5	$\times 10^{-4}$	CL=90%
Γ_{133}	$p \overline{\Lambda} \pi^-$		< 1.8	$\times 10^{-4}$	CL=90%
Γ_{134}	$\Delta^0 \overline{\Delta}^0$		< 1.5	$\times 10^{-3}$	CL=90%
Γ_{135}	$\Delta^{++} \Delta^{--}$		< 1.1	$\times 10^{-4}$	CL=90%
Γ_{136}	$\overline{\Sigma}_c^{--} \Delta^{++}$		< 1.0	$\times 10^{-3}$	CL=90%
Γ_{137}	$\Lambda_c^- p \pi^+ \pi^-$		(1.3 ± 0.6)	$\times 10^{-3}$	
Γ_{138}	$\Lambda_c^- p$		< 2.1	$\times 10^{-4}$	CL=90%
Γ_{139}	$\Lambda_c^- p \pi^0$		< 5.9	$\times 10^{-4}$	CL=90%
Γ_{140}	$\Lambda_c^- p \pi^+ \pi^- \pi^0$		< 5.07	$\times 10^{-3}$	CL=90%
Γ_{141}	$\Lambda_c^- p \pi^+ \pi^- \pi^+ \pi^-$		< 2.74	$\times 10^{-3}$	CL=90%

Lepton Family number (*LF*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

Γ_{142}	$\gamma \gamma$	*B1*		< 3.9	$\times 10^{-5}$	CL=90%
Γ_{143}	$e^+ e^-$	*B1*		< 5.9	$\times 10^{-6}$	CL=90%
Γ_{144}	$\mu^+ \mu^-$	*B1*		< 6.8	$\times 10^{-7}$	CL=90%
Γ_{145}	$K^0 e^+ e^-$	*B1*		< 3.0	$\times 10^{-4}$	CL=90%
Γ_{146}	$K^0 \mu^+ \mu^-$	*B1*		< 3.6	$\times 10^{-4}$	CL=90%
Γ_{147}	$K^*(892)^0 e^+ e^-$	*B1*		< 2.9	$\times 10^{-4}$	CL=90%
Γ_{148}	$K^*(892)^0 \mu^+ \mu^-$	*B1*		< 2.3	$\times 10^{-5}$	CL=90%
Γ_{149}	$K^*(892)^0 \nu \overline{\nu}$	*B1*		< 1.0	$\times 10^{-3}$	CL=90%
Γ_{150}	$e^\pm \mu^\mp$	*LF*	[c]	< 5.9	$\times 10^{-6}$	CL=90%
Γ_{151}	$e^\pm \tau^\mp$	*LF*	[c]	< 5.3	$\times 10^{-4}$	CL=90%
Γ_{152}	$\mu^\pm \tau^\mp$	*LF*	[c]	< 8.3	$\times 10^{-4}$	CL=90%

[a] An ℓ indicates an e or a μ mode, not a sum over these modes.

[b] B^0 and B_s^0 contributions not separated. Limit is on weighted average of the two decay rates.

[c] The value is for the sum of the charge states of particle/antiparticle states indicated.

B^0 BRANCHING RATIOS

For branching ratios in which the charge of the decaying B is not determined, see the $B^{\pm}$ section.

$\Gamma(\ell^+\nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.105 ±0.008 OUR AVERAGE			
0.1078±0.0060±0.0069	[31] ARTUSO 97	CLE2	$e^+e^- \to \Upsilon(4S)$
0.093 ±0.011 ±0.015	ALBRECHT 94	ARG	$e^+e^- \to \Upsilon(4S)$
0.099 ±0.030 ±0.009	HENDERSON 92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.109 ±0.007 ±0.011	ATHANAS 94	CLE2	Sup. by ARTUSO 97

[31] ARTUSO 97 uses partial reconstruction of $B \to D^*\ell\nu_\ell$ and inclusive semileptonic branching ratio from BARISH 96B (0.1049 ± 0.0017 ± 0.0043).

$\Gamma(D^-\ell^+\nu_\ell)/\Gamma_{\text{total}}$ Γ_2/Γ

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0200±0.0025 OUR AVERAGE			
0.0187±0.0015±0.0032	[32] ATHANAS 97	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0235±0.0020±0.0044	[33] BUSKULIC 97	ALEP	$e^+e^- \to Z$
0.018 ±0.006 ±0.003	[34] FULTON 91	CLEO	$e^+e^- \to \Upsilon(4S)$
0.020 ±0.007 ±0.006	[35] ALBRECHT 89J	ARG	$e^+e^- \to \Upsilon(4S)$

[32] ATHANAS 97 uses missing energy and missing momentum to reconstruct neutrino.

[33] BUSKULIC 97 assumes fraction (B^+) = fraction (B^0) = (37.8 ± 2.2)% and PDG 96 values for B lifetime and branching ratio of D^* and D decays.

[34] FULTON 91 assumes assuming equal production of B^0 and B^+ at the $\Upsilon(4S)$ and uses Mark III D and D^* branching ratios.

[35] ALBRECHT 89J reports 0.018 ± 0.006 ± 0.005. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$).

$\Gamma(D^*(2010)^-\ell^+\nu_\ell)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0460±0.0027 OUR AVERAGE				
0.0508±0.0021±0.0066		[36] ACKERSTAFF 97G	OPAL	$e^+e^- \to Z$
0.0553±0.0026±0.0052		[37] BUSKULIC 97	ALEP	$e^+e^- \to Z$
0.0552±0.0017±0.0068		[38] ABREU 96P	DLPH	$e^+e^- \to Z$
0.0449±0.0032±0.0039	376	[39] BARISH 95	CLE2	$e^+e^- \to \Upsilon(4S)$
0.045 ±0.003 ±0.004		[40] ALBRECHT 94	ARG	$e^+e^- \to \Upsilon(4S)$
0.047 ±0.005 ±0.005	235	[41] ALBRECHT 93	ARG	$e^+e^- \to \Upsilon(4S)$
0.040 ±0.004 ±0.006		[42] BORTOLETTO 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0518±0.0030±0.0062	410	[43] BUSKULIC 95N	ALEP	Sup. by BUSKULIC 97
seen	398	[44] SANGHERA 93	CLE2	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.018 ±0.014		[45] ANTREASYAN 90B	CBAL	$e^+e^- \to \Upsilon(4S)$
		[46] ALBRECHT 89C	ARG	$e^+e^- \to \Upsilon(4S)$
0.060 ±0.010 ±0.014		[47] ALBRECHT 89J	ARG	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.012 ±0.019	47	[48] ALBRECHT 87J	ARG	$e^+e^- \to \Upsilon(4S)$

[36] ACKERSTAFF 97G assumes fraction (B^+) = fraction (B^0) = (37.8 ± 2.2)% and PDG 96 values for B lifetime and branching ratio of D^* and D decays.

[37] BUSKULIC 97 assumes fraction (B^+) = fraction (B^0) = (37.8 ± 2.2)% and PDG 96 values for B lifetime and D^* and D branching fractions.

[38] ABREU 96P result is the average of two methods using exclusive and partial D^* reconstruction.

[39] BARISH 95 use B($D^0 \to K^-\pi^+$) = (3.91 ± 0.08 ± 0.17)% and B($D^{*+} \to D^0\pi^+$) = (68.1 ± 1.0 ± 1.3)%.

[40] ALBRECHT 94 assumes B($D^{*+} \to D^0\pi^+$) = 68.1 ± 1.0 ± 1.3%. Uses partial reconstruction of D^{*+} and is independent of D^0 branching ratios.

[41] ALBRECHT 93 reports 0.052 ± 0.005 ± 0.006. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$). We have taken their average e and μ value. They also obtain $\alpha = 2{*}\Gamma^0/(\Gamma^- + \Gamma^+) - 1 = 1.1 \pm 0.4 \pm 0.2$, $A_{AF} = 3/4{*}(\Gamma^- - \Gamma^+)/\Gamma = 0.2 \pm 0.08 \pm 0.06$ and a value of $|V_{cb}|$ = 0.036–0.045 depending on model assumptions.

[42] We have taken average of the the BORTOLETTO 89B values for electrons and muons, 0.046 ± 0.005 ± 0.007. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$). The measurement suggests a D^* polarization parameter value $\alpha = 0.65 \pm 0.66 \pm 0.25$.

[43] BUSKULIC 95N assumes fraction (B^+) = fraction (B^0) = 38.2 ± 1.3 ± 2.2% and τ_{B^0} = 1.58 ± 0.06 ps. $\Gamma(D^{*-}\ell^+\nu_\ell)$/total = [5.18 − 0.13(fraction(B^0)−38.2)−1.5(τ_{B^0} − 1.58)]%.

[44] Combining $\overline{D}^{*0}\ell^+\nu_\ell$ and $\overline{D}^{*-}\ell^+\nu_\ell$ SANGHERA 93 test $V-A$ structure and fit the decay angular distributions to obtain $A_{FB} = 3/4{*}(\Gamma^- - \Gamma^+)/\Gamma = 0.14 \pm 0.06 \pm 0.03$. Assuming a value of V_{cb}, they measure V, A_1, and A_2, the three form factors for the $D^*\ell\nu_\ell$ decay, where results are slightly dependent on model assumptions.

[45] ANTREASYAN 90B is average over B and $\overline{D}^*(2010)$ charge states.

[46] The measurement of ALBRECHT 89C suggests a D^* polarization γ_L/γ_T of 0.85 ± 0.45. or $\alpha = 0.7 \pm 0.9$.

[47] ALBRECHT 89J is ALBRECHT 87J value rescaled using B($D^*(2010)^- \to D^0\pi^-$) = 0.57 ± 0.04 ± 0.04. Superseded by ALBRECHT 93.

[48] ALBRECHT 87J assume μ-e universality, the B($\Upsilon(4S) \to B^0\overline{B}^0$) = 0.45, the B($D^0 \to K^-\pi^+$) = (0.042 ± 0.004 ± 0.004), and the B($D^*(2010)^- \to D^0\pi^-$) = 0.49 ± 0.08. Superseded by ALBRECHT 89J.

$\Gamma(\rho^-\ell^+\nu_\ell)/\Gamma_{\text{total}}$ Γ_4/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$2.5\pm0.4^{+0.7}_{-0.9}$		[49] ALEXANDER 96T	CLE2	$e+\ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.1	90	[50] BEAN 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[49] ALEXANDER 96T gives systematic errors $^{+0.5}_{-0.7}$ ± 0.5 where the second error reflects the estimated model dependence. We combine these in quadrature. Assumes isospin symmetry: $\Gamma(B^0 \to \rho^-\ell^+\nu_\ell) = 2 \times \Gamma(B^+ \to \rho^0\ell^+\nu_\ell) \sim 2 \times \Gamma(B^+ \to \omega\ell^+\nu_\ell)$.

[50] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\rho^0\ell^+\nu_\ell)$ and $\Gamma(\omega\ell^+\nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \to (\omega \text{ or } \rho^0)\ell^+\nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| <$ 0.08–0.13 at 90% CL is derived as well.

$\Gamma(\pi^-\ell^+\nu_\ell)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
1.8±0.4±0.4	[51] ALEXANDER 96T	CLE2	$e+\ e^- \to \Upsilon(4S)$

[51] ALEXANDER 96T gives systematic errors ±0.3 ± 0.2 where the second error reflects the estimated model dependence. We combine these in quadrature. Assumes isospin symmetry: $\Gamma(B^0 \to \pi^-\ell^+\nu_\ell) = 2 \times \Gamma(B^+ \to \pi^0\ell^+\nu_\ell)$.

$\Gamma(\pi^-\mu^+\nu_\mu)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
seen	[52] ALBRECHT 91C	ARG

[52] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \to u$ transition.

$\Gamma(K^+ \text{anything})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.78±0.8	[53] ALBRECHT 96D	ARG	$e^+e^- \to \Upsilon(4S)$

[53] Average multiplicity.

$\Gamma(D^-\pi^+)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0030±0.0004 OUR AVERAGE				
0.0029±0.0004±0.0002	81	[54] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0027±0.0006±0.0005		[55] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0048±0.0011±0.0011	22	[56] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0051^{+0.0028}_{-0.0025}{}^{+0.0013}_{-0.0012}$	4	[57] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0031±0.0013±0.0010	7	[56] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[54] ALAM 94 reports [B($B^0 \to D^-\pi^+$) × B($D^+ \to K^-\pi^+\pi^+$)] = 0.000265 ± 0.000032 ± 0.000023. We divide by our best value B($D^+ \to K^-\pi^+\pi^+$) = (9.0 ± 0.6) × 10^{-2}. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[55] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[56] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J which assumes 50:50.

[57] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

$\Gamma(D^-\rho^+)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0079±0.0014 OUR AVERAGE				
0.0078±0.0013±0.0005	79	[58] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.009 ±0.005 ±0.003	9	[59] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022 ±0.012 ±0.009	6	[59] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[58] ALAM 94 reports [B($B^0 \to D^-\rho^+$) × B($D^+ \to K^-\pi^+\pi^+$)] = 0.000704 ± 0.000096 ± 0.000070. We divide by our best value B($D^+ \to K^-\pi^+\pi^+$) = (9.0 ± 0.6) × 10^{-2}. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[59] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J which assumes 50:50.

$\Gamma(\overline{D}^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0016	90		[60] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.007	90		[61] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.034	90		[62] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.07 ±0.05		5	[63] BEHRENDS 83	CLEO	$e^+e^- \to \Upsilon(4S)$

[60] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[61] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$

followed by $D_0^*(2340) \rightarrow D^0\pi$ is < 0.0001 at 90% CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \rightarrow D^0\pi$ is < 0.0004 at 90% CL.

[62] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%. $B(D^0 \rightarrow K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-) = (9.1 \pm 0.8 \pm 0.8)\%$ were used.

[63] Corrected by us using assumptions: $B(D^0 \rightarrow K^-\pi^+) = (0.042 \pm 0.006)$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 50\%$. The product branching ratio is $B(B^0 \rightarrow \overline{D}^0\pi^+\pi^-)B(\overline{D}^0 \rightarrow K^+\pi^-) = (0.39 \pm 0.26) \times 10^{-2}$.

$\Gamma(D^*(2010)^-\pi^+)/\Gamma_{total}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.00276±0.00021 OUR AVERAGE				
0.00281±0.00024±0.00005		[64] BRANDENB... 98	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0026 ±0.0003 ±0.0004	82	[65] ALAM 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0033 ±0.0010 ±0.0001		[66] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.00234±0.00087±0.00005	12	[67] ALBRECHT 90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.00234^{+0.00148}_{-0.00109}\pm0.00005$	5	[68] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.010 ±0.004 ±0.001	8	[69] AKERS 94J	OPAL	$e^+e^- \rightarrow Z$
0.0027 ±0.0014 ±0.0010	5	[70] ALBRECHT 87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.0035 ±0.002 ±0.002		[71] ALBRECHT 86F	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.017 ±0.005 ±0.005	41	[72] GILES 84	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[64] BRANDENBURG 98 assume equal production of B^+ and B^0 at $\Upsilon(4S)$ and use the D^* reconstruction technique. The first error is their experiment's error and the second error is the systematic error from the PDG 96 value of $B(D^* \rightarrow D\pi)$.

[65] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \rightarrow D^0\pi^+)$ and absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

[66] BORTOLETTO 92 reports $0.0040 \pm 0.0010 \pm 0.0007$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[67] ALBRECHT 90J reports $0.0028 \pm 0.0009 \pm 0.0006$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[68] BEBEK 87 reports $0.0028^{+0.0015+0.0010}_{-0.0012-0.0006}$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92 and ALBRECHT 90J.

[69] Assumes $B(Z \rightarrow b\overline{b}) = 0.217$ and 38% B_d production fraction.

[70] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \rightarrow B^+B^-) = 55\%$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

[71] ALBRECHT 86F uses pseudomass that is independent of D^0 and D^+ branching ratios.

[72] Assumes $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. Assumes $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 0.40 \pm 0.02$ Does not depend on D branching ratios.

$\Gamma(D^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{12}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0080±0.0021±0.0014	[73] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[73] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma((D^-\pi^+\pi^+\pi^-)\text{ nonresonant})/\Gamma_{total}$ Γ_{13}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0039±0.0014±0.0013	[74] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[74] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^-\pi^+\rho^0)/\Gamma_{total}$ Γ_{14}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0011±0.0009±0.0004	[75] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[75] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^-a_1(1260)^+)/\Gamma_{total}$ Γ_{15}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0060±0.0022±0.0024	[76] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[76] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^-\pi^+\pi^0)/\Gamma_{total}$ Γ_{16}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0150±0.0051±0.0003	51	[77] ALBRECHT 90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.015 ±0.008 ±0.008	8	[78] ALBRECHT 87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[77] ALBRECHT 90J reports $0.018 \pm 0.004 \pm 0.005$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[78] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \rightarrow B^+B^-) = 55\%$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^-\rho^+)/\Gamma_{total}$ Γ_{17}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0067±0.0033 OUR AVERAGE				
0.0159±0.0112±0.0003		[79] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.0058±0.0035±0.0001	19	[80] ALBRECHT 90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0074±0.0010±0.0014	76	[81,82] ALAM 94	CLE2	Sup. by JESSOP 97
$0.081 \pm0.029 ^{+0.059}_{-0.024}$	19	[83] CHEN 85	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[79] BORTOLETTO 92 reports $0.019 \pm 0.008 \pm 0.011$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[80] ALBRECHT 90J reports $0.007 \pm 0.003 \pm 0.003$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[81] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \rightarrow D^0\pi^+)$ and absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

[82] This decay is nearly completely longitudinally polarized, $\Gamma_L/\Gamma = (93 \pm 5 \pm 5)\%$, as expected from the factorization hypothesis (ROSNER 90). The nonresonant $\pi^+\pi^0$ contribution under the ρ^+ is less than 9% at 90% CL.

[83] Uses $B(D^* \rightarrow D^0\pi^+) = 0.6 \pm 0.15$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 0.4$. Does not depend on D branching ratios.

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{18}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0076±0.0017 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
0.0063±0.0010±0.0011		49	[84,85] ALAM 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0133±0.0036±0.0003			[86] BORTOLETTO92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.0100±0.0040±0.0002		26	[87] ALBRECHT 90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.033 ±0.009 ±0.016		27	[88] ALBRECHT 87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<0.042	90		[89] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[84] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \rightarrow D^0\pi^+)$ and absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

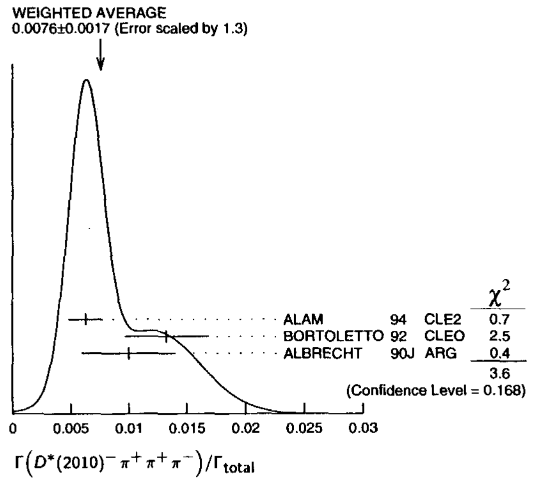
[85] The three pion mass is required to be between 1.0 and 1.6 GeV consistent with an a_1 meson. (If this channel is dominated by a_1^+, the branching ratio for $\overline{D}^{*-}a_1^+$ is twice that for $\overline{D}^{*-}\pi^+\pi^+\pi^-$.)

[86] BORTOLETTO 92 reports $0.0159 \pm 0.0028 \pm 0.0037$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[87] ALBRECHT 90J reports $0.012 \pm 0.003 \pm 0.004$ for $B(D^*(2010)^+ \rightarrow D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \rightarrow D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[88] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \rightarrow B^+B^-) = 55\%$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

[89] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.



$\Gamma((D^*(2010)^-\pi^+\pi^+\pi^-)\text{ nonresonant})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.0000\pm0.0019\pm0.0016$	[90] BORTOLETTO92	CLEO	$e^+e^-\to\Upsilon(4S)$

[90] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(D^*(2010)^-\pi^+\rho^0)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.0057\pm0.0031\pm0.0001$	[91] BORTOLETTO92	CLEO	$e^+e^-\to\Upsilon(4S)$

[91] BORTOLETTO 92 reports $0.0068\pm0.0032\pm0.0021$ for $B(D^*(2010)^+\to D^0\pi^+)=0.57\pm0.06$. We rescale to our best value $B(D^*(2010)^+\to D^0\pi^+)=(68.3\pm1.4)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^-a_1(1260)^+)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0130 ± 0.0027 OUR AVERAGE			
$0.0126\pm0.0020\pm0.0022$	[92,93] ALAM 94	CLE2	$e^+e^-\to\Upsilon(4S)$
$0.0150\pm0.0069\pm0.0003$	[94] BORTOLETTO92	CLEO	$e^+e^-\to\Upsilon(4S)$

[92] ALAM 94 value is twice their $\Gamma(D^*(2010)^-\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ value based on their observation that the three pions are dominantly in the $a_1(1260)$ mass range 1.0 to 1.6 GeV.

[93] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+\to D^0\pi^+)$ and absolute $B(D^0\to K^-\pi^+)$ and the PDG 1992 $B(D^0\to K^-\pi^+\pi^0)/B(D^0\to K^-\pi^+)$ and $B(D^0\to K^-\pi^+\pi^+\pi^-)/B(D^0\to K^-\pi^+)$.

[94] BORTOLETTO 92 reports $0.018\pm0.006\pm0.006$ for $B(D^*(2010)^+\to D^0\pi^+)=0.57\pm0.06$. We rescale to our best value $B(D^*(2010)^+\to D^0\pi^+)=(68.3\pm1.4)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.034\pm0.018\pm0.001$	28	[95] ALBRECHT 90J	ARG	$e^+e^-\to\Upsilon(4S)$

[95] ALBRECHT 90J reports $0.041\pm0.015\pm0.016$ for $B(D^*(2010)^+\to D^0\pi^+)=0.57\pm0.06$. We rescale to our best value $B(D^*(2010)^+\to D^0\pi^+)=(68.3\pm1.4)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}{}_2^*(2460)^-\pi^+)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	[96] ALAM 94	CLE2	$e^+e^-\to\Upsilon(4S)$

[96] ALAM 94 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0\to K^-\pi^+)$ and $B(D_2^*(2460)^+\to D^0\pi^+)=30\%$.

$\Gamma(\overline{D}{}_2^*(2460)^-\rho^+)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0049	90	[97] ALAM 94	CLE2	$e^+e^-\to\Upsilon(4S)$

[97] ALAM 94 assumesequal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0\to K^-\pi^+)$ and $B(D_2^*(2460)^+\to D^0\pi^+)=30\%$.

$\Gamma(D^-D_s^+)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0080 ± 0.0030 OUR AVERAGE				
$0.0084\pm0.0030^{+0.0020}_{-0.0021}$		[98] GIBAUT 96	CLE2	$e^+e^-\to\Upsilon(4S)$
$0.013\ \pm0.011\ \pm0.003$		[99] ALBRECHT 92G	ARG	$e^+e^-\to\Upsilon(4S)$
$0.007\ \pm0.004\ \pm0.002$		[100] BORTOLETTO92	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.012\ \pm0.007$	3	[101] BORTOLETTO90	CLEO	$e^+e^-\to\Upsilon(4S)$

[98] GIBAUT 96 reports $0.0087\pm0.0024\pm0.0020$ for $B(D_s^+\to\phi\pi^+)=0.035$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[99] ALBRECHT 92G reports $0.017\pm0.013\pm0.006$ for $B(D_s^+\to\phi\pi^+)=0.027$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ branching ratios, e.g., $B(D^+\to K^-\pi^+\pi^+)=7.7\pm1.0\%$.

[100] BORTOLETTO 92 reports $0.0080\pm0.0045\pm0.0030$ for $B(D_s^+\to\phi\pi^+)=0.030\pm0.011$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[101] BORTOLETTO 90 assume $B(D_s\to\phi\pi^+)=2\%$. Superseded by BORTOLETTO 92.

$\Gamma(D^*(2010)^-D_s^+)/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0096 ± 0.0034 OUR AVERAGE				
$0.0090\pm0.0027\pm0.0022$		[102] GIBAUT 96	CLE2	$e^+e^-\to\Upsilon(4S)$
$0.010\ \pm0.008\ \pm0.003$		[103] ALBRECHT 92G	ARG	$e^+e^-\to\Upsilon(4S)$
$0.013\ \pm0.008\ \pm0.003$		[104] BORTOLETTO92	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.024\ \pm0.014$	3	[105] BORTOLETTO90	CLEO	$e^+e^-\to\Upsilon(4S)$

[102] GIBAUT 96 reports $0.0093\pm0.0023\pm0.0016$ for $B(D_s^+\to\phi\pi^+)=0.035$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[103] ALBRECHT 92G reports $0.014\pm0.010\pm0.003$ for $B(D_s^+\to\phi\pi^+)=0.027$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ and $D^*(2010)^+$ branching ratios, e.g., $B(D^0\to K^-\pi^+)=3.71\pm0.25\%$, $B(D^+\to K^-\pi^+\pi^+)=7.1\pm1.0\%$, and $B(D^*(2010)^+\to D^0\pi^+)=55\pm4\%$.

[104] BORTOLETTO 92 reports $0.016\pm0.009\pm0.006$ for $B(D_s^+\to\phi\pi^+)=0.030\pm0.011$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

[105] BORTOLETTO 90 assume $B(D_s\to\phi\pi^+)=2\%$. Superseded by BORTOLETTO 92.

$\Gamma(D^-D_s^{*+})/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.010 ± 0.005 OUR AVERAGE			
$0.010\pm0.004\pm0.002$	[106] GIBAUT 96	CLE2	$e^+e^-\to\Upsilon(4S)$
$0.020\pm0.014\pm0.005$	[107] ALBRECHT 92G	ARG	$e^+e^-\to\Upsilon(4S)$

[106] GIBAUT 96 reports $0.0100\pm0.0035\pm0.0022$ for $B(D_s^+\to\phi\pi^+)=0.035$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[107] ALBRECHT 92G reports $0.027\pm0.017\pm0.009$ for $B(D_s^+\to\phi\pi^+)=0.027$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ branching ratios, e.g., $B(D^+\to K^-\pi^+\pi^+)=7.7\pm1.0\%$.

$[\Gamma(D^*(2010)^-D_s^+)+\Gamma(D^*(2010)^-D_s^{*+})]/\Gamma_{\text{total}}$ $(\Gamma_{26}+\Gamma_{28})/\Gamma$

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
$4.15\pm1.11^{+0.99}_{-1.02}$	22	[108] BORTOLETTO90	CLEO	$e^+e^-\to\Upsilon(4S)$

[108] BORTOLETTO 90 reports 7.5 ± 2.0 for $B(D_s^+\to\phi\pi^+)=0.02$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^*(2010)^-D_s^{*+})/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.020 ± 0.007 OUR AVERAGE			
$0.020\pm0.006\pm0.005$	[109] GIBAUT 96	CLE2	$e^+e^-\to\Upsilon(4S)$
$0.019\pm0.011\pm0.005$	[110] ALBRECHT 92G	ARG	$e^+e^-\to\Upsilon(4S)$

[109] GIBAUT 96 reports $0.0203\pm0.0050\pm0.0036$ for $B(D_s^+\to\phi\pi^+)=0.035$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[110] ALBRECHT 92G reports $0.026\pm0.014\pm0.006$ for $B(D_s^+\to\phi\pi^+)=0.027$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=(3.6\pm0.9)\times10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ and $D^*(2010)^+$ branching ratios, e.g., $B(D^0\to K^-\pi^+)=3.71\pm0.25\%$, $B(D^+\to K^-\pi^+\pi^+)=7.1\pm1.0\%$, and $B(D^*(2010)^+\to D^0\pi^+)=55\pm4\%$.

$\Gamma(D_s^+\pi^-)/\Gamma_{\text{total}}$ Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00028	90	[111] ALEXANDER 93B	CLE2	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0013	90	[112] BORTOLETTO90	CLEO	$e^+e^-\to\Upsilon(4S)$

[111] ALEXANDER 93B reports $<2.7\times10^{-4}$ for $B(D_s^+\to\phi\pi^+)=0.037$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=0.036$.

[112] BORTOLETTO 90 assume $B(D_s\to\phi\pi^+)=2\%$.

$\Gamma(D_s^{*+}\pi^-)/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[113] ALEXANDER 93B	CLE2	$e^+e^-\to\Upsilon(4S)$

[113] ALEXANDER 93B reports $<4.4\times10^{-4}$ for $B(D_s^+\to\phi\pi^+)=0.037$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=0.036$.

$[\Gamma(D_s^+\pi^-)+\Gamma(D_s^-K^+)]/\Gamma_{\text{total}}$ $(\Gamma_{29}+\Gamma_{35})/\Gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[114] ALBRECHT 93E	ARG	$e^+e^-\to\Upsilon(4S)$

[114] ALBRECHT 93E reports $<1.7\times10^{-3}$ for $B(D_s^+\to\phi\pi^+)=0.027$. We rescale to our best value $B(D_s^+\to\phi\pi^+)=0.036$.

$[\Gamma(D_s^{*+}\pi^-)+\Gamma(D_s^{*-}K^+)]/\Gamma_{\rm total}$ — $(\Gamma_{30}+\Gamma_{36})/\Gamma$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0009	90	[115] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[115] ALBRECHT 93E reports $< 1.2 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\rho^-)/\Gamma_{\rm total}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0007	90	[116] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0016	90	[117] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[116] ALEXANDER 93B reports $< 6.6 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[117] ALBRECHT 93E reports $< 2.2 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\rho^-)/\Gamma_{\rm total}$ — Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0008	90	[118] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0019	90	[119] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[118] ALEXANDER 93B reports $< 7.4 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[119] ALBRECHT 93E reports $< 2.5 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+ a_1(1260)^-)/\Gamma_{\rm total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0026	90	[120] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[120] ALBRECHT 93E reports $< 3.5 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+} a_1(1260)^-)/\Gamma_{\rm total}$ — Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	[121] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[121] ALBRECHT 93E reports $< 2.9 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^- K^+)/\Gamma_{\rm total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00024	90	[122] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0013	90	[123] BORTOLETTO 90	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[122] ALEXANDER 93B reports $< 2.3 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[123] BORTOLETTO 90 assume $B(D_s \rightarrow \phi\pi^+) = 2\%$.

$\Gamma(D_s^{*-} K^+)/\Gamma_{\rm total}$ — Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00017	90	[124] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[124] ALEXANDER 93B reports $< 1.7 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^- K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0010	90	[125] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0034	90	[126] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[125] ALEXANDER 93B reports $< 9.7 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[126] ALBRECHT 93E reports $< 4.6 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-} K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0011	90	[127] ALEXANDER 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.004	90	[128] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[127] ALEXANDER 93B reports $< 11.0 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[128] ALBRECHT 93E reports $< 5.8 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^-\pi^+ K^0)/\Gamma_{\rm total}$ — Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	[129] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[129] ALBRECHT 93E reports $< 7.3 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-}\pi^+ K^0)/\Gamma_{\rm total}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0031	90	[130] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[130] ALBRECHT 93E reports $< 4.2 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^-\pi^+ K^*(892)^0)/\Gamma_{\rm total}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	90	[131] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[131] ALBRECHT 93E reports $< 5.0 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-}\pi^+ K^*(892)^0)/\Gamma_{\rm total}$ — Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0020	90	[132] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[132] ALBRECHT 93E reports $< 2.7 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(\overline{D}^0\pi^0)/\Gamma_{\rm total}$ — Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00012	90	[133] NEMATI 98	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00048	90	[134] ALAM 94	CLE2	Repl. by NEMATI 98

[133] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[134] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

$\Gamma(\overline{D}^0\rho^0)/\Gamma_{\rm total}$ — Γ_{44}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.00039	90		[135] NEMATI 98	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.00055	90		[136] ALAM 94	CLE2	Repl. by NEMATI 98
<0.0006	90		[137] BORTOLETTO 92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<0.0027	90	4	[138] ALBRECHT 88K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[135] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[136] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

[137] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[138] ALBRECHT 88K reports < 0.003 assuming $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. We rescale to 50%.

$\Gamma(\overline{D}^0\eta)/\Gamma_{\rm total}$ — Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00013	90	[139] NEMATI 98	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00068	90	[140] ALAM 94	CLE2	Repl. by NEMATI 98

[139] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[140] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

$\Gamma(\overline{D}^0\eta')/\Gamma_{\rm total}$ — Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00094	90	[141] NEMATI 98	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00086	90	[142] ALAM 94	CLE2	Repl. by NEMATI 98

[141] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[142] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^-\pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^-\pi^+\pi^0)/B(D^0 \rightarrow K^-\pi^+)$ and $B(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/B(D^0 \rightarrow K^-\pi^+)$.

$\Gamma(\overline{D}^0\omega)/\Gamma_{\text{total}}$ — Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00051	90	[143] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00063	90	[144] ALAM 94	CLE2	Repl. by NEMATI 98

[143] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[144] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0\pi^0)/\Gamma_{\text{total}}$ — Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00044	90	[145] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00097	90	[146] ALAM 94	CLE2	Repl. by NEMATI 98

[145] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[146] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0\rho^0)/\Gamma_{\text{total}}$ — Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00056	90	[147] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00117	90	[148] ALAM 94	CLE2	Repl. by NEMATI 98

[147] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[148] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0\eta)/\Gamma_{\text{total}}$ — Γ_{50}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00026	90	[149] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.00069	90	[150] ALAM 94	CLE2	Repl. by NEMATI 98

[149] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[150] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0\eta')/\Gamma_{\text{total}}$ — Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0014	90	BRANDENB... 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0019	90	[151] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
<0.0027	90	[152] ALAM 94	CLE2	Repl. by NEMATI 98

[151] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[152] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0\omega)/\Gamma_{\text{total}}$ — Γ_{52}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00074	90	[153] NEMATI 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0021	90	[154] ALAM 94	CLE2	Repl. by NEMATI 98

[153] NEMATI 98 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the PDG 96 values for D^0, D^{*0}, η, η', and ω branching fractions.

[154] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(D^*(2010)^+D^*(2010)^-)/\Gamma_{\text{total}}$ — Γ_{53}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.2\times10^{-3}$	90	[155] ASNER 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[155] ASNER 97 at CLEO observes 1 event with an expected background of 0.022 ± 0.011. This correcsponds to a branching ratio of $(5.3^{+7.1}_{-3.7} \pm 1.0) \times 10^{-4}$.

$\Gamma(D^*(2010)^+D^-)/\Gamma_{\text{total}}$ — Γ_{54}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.8\times10^{-3}$	90	ASNER 97	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(D^+D^*(2010)^-)/\Gamma_{\text{total}}$ — Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2\times10^{-3}$	90	ASNER 97	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(J/\psi(1S)K^0)/\Gamma_{\text{total}}$ — Γ_{56}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
8.9 ±1.2 OUR AVERAGE					
$8.5\,^{+1.4}_{-1.2}\pm0.6$			[156] JESSOP 97	CLE2	$e^+e^- \to \Upsilon(4S)$
11.5 ±2.3 ±1.7			[157] ABE 96H	CDF	$p\overline{p}$ at 1.8 TeV
6.87 ±4.03 ±0.22			[158] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
9.2 ±7.1 ±0.3		2	[159] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.5 ±2.4 ±0.8		10	[158] ALAM 94	CLE2	Sup. by JESSOP 97
<50	90		ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[156] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[157] ABE 96H assumes that $B(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$.

[158] BORTOLETTO 92 reports 6 ± 3 ± 2 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[159] ALBRECHT 90J reports 8 ± 6 ± 2 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)K^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{57}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.00115±0.00055±0.00004			[160] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90		[161] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<0.0063	90	2	GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[160] BORTOLETTO 92 reports 0.0010 ± 0.0004 ± 0.0003 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[161] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. $K\pi$ system is specifically selected as nonresonant.

$\Gamma(J/\psi(1S)K^*(892)^0)/\Gamma_{\text{total}}$ — Γ_{58}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.00135±0.00018 OUR AVERAGE				
0.00132 ±0.00017 ±0.00017		[162] JESSOP 97	CLE2	$e^+e^- \to \Upsilon(4S)$
0.00136 ±0.00027 ±0.00022		[163] ABE 96H	CDF	$p\overline{p}$ at 1.8 TeV
0.00126 ±0.00065 ±0.00004		[164] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.00126 ±0.00059 ±0.00004	6	[165] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
0.0040 ±0.0018 ±0.0001	5	[166] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.00169 ±0.00031 ±0.00018	29	[167] ALAM 94	CLE2	Sup. by JESSOP 97
		[168] ALBRECHT 94G	ARG	$e^+e^- \to \Upsilon(4S)$
0.0040 ±0.0030		[169] ALBAJAR 91E	UA1	$E^{p\overline{p}}_{\text{cm}} = 630$ GeV
0.0033 ±0.0018	5	[170] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
0.0041 ±0.0018	5	[171] ALAM 86	CLEO	Repl. by BEBEK 87

[162] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[163] ABE 96H assumes that $B(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$.

[164] BORTOLETTO 92 reports 0.0011 ± 0.0005 ± 0.0003 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[165] ALBRECHT 90J reports 0.0011 ± 0.0005 ± 0.0002 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[166] BEBEK 87 reports 0.0035 ± 0.0016 ± 0.0003 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Updated in BORTOLETTO 92 to use the same assumptions.

[167] The neutral and charged B events together are predominantly longitudinally polarized, $\Gamma_L/\Gamma = 0.080 \pm 0.08 \pm 0.05$. This can be compared with a prediction using HQET, 0.73 (KRAMER 92). This polarization indicates that the $B \to \psi K^*$ decay is dominated by the $CP = -1$ CP eigenstate. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[168] ALBRECHT 94G measures the polarization in the vector-vector decay to be predominantly longitudinal, $\Gamma_T/\Gamma = 0.03 \pm 0.16 \pm 0.15$ making the neutral decay a CP eigenstate when the K^{*0} decays through $K^0_S\pi^0$.

[169] ALBAJAR 91E assumes B^0_d production fraction of 36%.

[170] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

[171] ALAM 86 assumes $B^\pm/B^0$ ratio is 60/40. The observation of the decay $B^+ \to J/\psi K^*(892)^+$ (HAAS 85) has been retracted in this paper.

$\Gamma(J/\psi(1S)K^*(892)^0)/\Gamma(J/\psi(1S)K^0)$ — Γ_{58}/Γ_{56}

VALUE	DOCUMENT ID	TECN	COMMENT
1.39±0.36±0.10	ABE 96Q	CDF	$p\overline{p}$

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\text{total}}$ Γ_{59}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<5.8 \times 10^{-5}$	90		BISHAI	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<3.2 \times 10^{-4}$	90		[172] ACCIARRI	97C	L3	
$<6.9 \times 10^{-3}$	90	1	[173] ALEXANDER	95	CLE2	Sup. by BISHAI 96

[172] ACCIARRI 97C assumes B^0 production fraction (39.5 ± 4.0%) and B_s (12.0 ± 3.0%).

[173] Assumes equal production of B^+B^- and $B^0\overline{B}^0$ on $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$ Γ_{60}/Γ

VALUE	CL%	DOCUMENT ID		TECN
$<1.2 \times 10^{-3}$	90	[174] ACCIARRI	97C	L3

[174] ACCIARRI 97C assumes B^0 production fraction (39.5 ± 4.0%) and B_s (12.0 ± 3.0%).

$\Gamma(J/\psi(1S)\rho^0)/\Gamma_{\text{total}}$ Γ_{61}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.5 \times 10^{-4}$	90	BISHAI	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(J/\psi(1S)\omega)/\Gamma_{\text{total}}$ Γ_{62}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.7 \times 10^{-4}$	90	BISHAI	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\psi(2S)K^0)/\Gamma_{\text{total}}$ Γ_{63}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0008	90	[175] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0015	90	[175] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.0028	90	[175] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[175] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^+\pi^-)/\Gamma_{\text{total}}$ Γ_{64}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	[176] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[176] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{65}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0014±0.0008±0.0004		[177] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0019	90	[177] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
<0.0023	90	[177] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[177] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^0)/\Gamma_{\text{total}}$ Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0027	90	[178] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[178] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{67}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0021	90	[179] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[179] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(K^+\pi^-)/\Gamma_{\text{total}}$ Γ_{68}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
$1.5^{+0.5}_{-0.4} \pm 0.14$		GODANG	98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$2.4^{+1.7}_{-1.1} \pm 0.2$		[180] ADAM	96D	DLPH	$e^+e^- \to Z$
< 1.7	90	ASNER	96	CLE2	Sup. by ADAM 96D
< 3.0	90	[181] BUSKULIC	96V	ALEP	$e^+e^- \to Z$
< 9	90	[182] ABREU	95N	DLPH	Sup. by ADAM 96D
< 8.1	90	[183] AKERS	94L	OPAL	$e^+e^- \to Z$
< 2.6	90	[184] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$
<18	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
< 9	90	[185] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<32	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[180] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$. Contributions from B^0 and B_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[181] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[182] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[183] Assumes $B(Z \to b\overline{b}) = 0.217$ and B_d^0 (B_s^0) fraction 39.5% (12%).

[184] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[185] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0\pi^0)/\Gamma_{\text{total}}$ Γ_{69}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.1 \times 10^{-5}$	90	GODANG	98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.0 \times 10^{-5}$	90	ASNER	96	CLE2	Rep. by GODANG 98

$\Gamma(\eta' K^0)/\Gamma_{\text{total}}$ Γ_{70}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$(4.7^{+2.7}_{-2.0} \pm 0.9) \times 10^{-5}$	BEHRENS	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta' K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{71}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.9 \times 10^{-5}$	90	BEHRENS	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{72}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.0 \times 10^{-5}$	90	BEHRENS	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta K^0)/\Gamma_{\text{total}}$ Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3 \times 10^{-5}$	90	BEHRENS	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$[\Gamma(K^+\pi^-) + \Gamma(\pi^+\pi^-)]/\Gamma_{\text{total}}$ $(\Gamma_{68}+\Gamma_{108})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$(1.9 \pm 0.6) \times 10^{-5}$ OUR AVERAGE					
$(2.8^{+1.5}_{-1.0} \pm 2.0) \times 10^{-5}$		[186] ADAM	96D	DLPH	$e^+e^- \to Z$
$(1.8^{+0.6+0.3}_{-0.5-0.4}) \times 10^{-5}$	17.2	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$(2.4^{+0.8}_{-0.7} \pm 0.2) \times 10^{-5}$		[187] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$

[186] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$. Contributions from B^0 and B_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[187] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_{74}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-6}$	90	GODANG	98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.6 \times 10^{-5}$		[188] ADAM	96D	DLPH	$e^+e^- \to Z$
$<0.4 \times 10^{-5}$	90	ASNER	96	CLE2	Repl. by GODANG 98
$<1.8 \times 10^{-5}$	90	[189] BUSKULIC	96V	ALEP	$e^+e^- \to Z$
$<1.2 \times 10^{-4}$	90	[190] ABREU	95N	DLPH	Sup. by ADAM 96D
$<0.7 \times 10^{-5}$	90	[191] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$

[188] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$. Contributions from B^0 and B_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[189] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[190] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[191] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(K^0\overline{K}^0)/\Gamma_{\text{total}}$ Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.7 \times 10^{-5}$	90	GODANG	98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\rho^-)/\Gamma_{\text{total}}$ Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.5 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{77}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\rho^0)/\Gamma_{\text{total}}$ Γ_{78}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.9 \times 10^{-5}$	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.2 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<5.0 \times 10^{-4}$	90	[192] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.064	90	[193] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[192] AVERY 89B reports $< 5.8 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[193] AVERY 87 reports < 0.08 assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0 f_0(980))/\Gamma_{\rm total}$ Γ_{79}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.6 \times 10^{-4}$	90	[194] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[194] AVERY 89B reports $< 4.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+ \pi^-)/\Gamma_{\rm total}$ Γ_{80}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.2 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
$<3.8 \times 10^{-4}$	90	[195] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.2 \times 10^{-4}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<5.6 \times 10^{-4}$	90	[196] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[195] AVERY 89B reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[196] AVERY 87 reports $< 7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0 \pi^0)/\Gamma_{\rm total}$ Γ_{81}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+ \pi^-)/\Gamma_{\rm total}$ Γ_{82}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.6 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0 K^+ K^-)/\Gamma_{\rm total}$ Γ_{83}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-3}$	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0 \phi)/\Gamma_{\rm total}$ Γ_{84}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.8 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<7.2 \times 10^{-4}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<4.2 \times 10^{-4}$	90	[197] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<1.0 \times 10^{-3}$	90	[198] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[197] AVERY 89B reports $< 4.9 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[198] AVERY 87 reports $< 1.3 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^- \pi^+ \pi^+ \pi^-)/\Gamma_{\rm total}$ Γ_{85}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.3 \times 10^{-4}$	90	[199] ADAM 96D	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.1 \times 10^{-4}$	90	[200] ABREU 95N	DLPH	Sup. by ADAM 96D

[199] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$. Contributions from B^0 and B_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[200] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

$\Gamma(K^*(892)^0 \pi^+ \pi^-)/\Gamma_{\rm total}$ Γ_{86}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-3}$	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0 \rho^0)/\Gamma_{\rm total}$ Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.6 \times 10^{-4}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.8 \times 10^{-4}$	90	[201] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<9.6 \times 10^{-4}$	90	[202] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[201] AVERY 89B reports $< 6.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[202] AVERY 87 reports $< 1.2 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0 f_0(980))/\Gamma_{\rm total}$ Γ_{88}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7 \times 10^{-4}$	90	[203] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[203] AVERY 89B reports $< 2.0 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^+ \pi^-)/\Gamma_{\rm total}$ Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^- a_1(1260)^+)/\Gamma_{\rm total}$ Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.3 \times 10^{-4}$	90	[204] ADAM 96D	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.9 \times 10^{-4}$	90	[205] ABREU 95N	DLPH	Sup. by ADAM 96D

[204] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$. Contributions from B^0 and B_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[205] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

$\Gamma(K^*(892)^0 K^+ K^-)/\Gamma_{\rm total}$ Γ_{91}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.1 \times 10^{-4}$	90	ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0 \phi)/\Gamma_{\rm total}$ Γ_{92}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.3 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.2 \times 10^{-4}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<3.8 \times 10^{-4}$	90	[206] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<3.8 \times 10^{-4}$	90	[207] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[206] AVERY 89B reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[207] AVERY 87 reports $< 4.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^0 \rho^0)/\Gamma_{\rm total}$ Γ_{93}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^0 \phi)/\Gamma_{\rm total}$ Γ_{94}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.0 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0 \rho^0)/\Gamma_{\rm total}$ Γ_{95}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0 \phi)/\Gamma_{\rm total}$ Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.4 \times 10^{-3}$	90	ALBRECHT 91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0 \gamma)/\Gamma_{\rm total}$ Γ_{97}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$4.0 \pm 1.7 \pm 0.8$		8	[208] AMMAR 93	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 21	90		[209] ADAM 96D	DLPH	$e^+e^- \to Z$
< 42	90		ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$
< 24	90		[210] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<210	90		AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[208] AMMAR 93 observed 6.6 ± 2.8 events above background.

[209] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[210] AVERY 89B reports $< 2.8 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1270)^0 \gamma)/\Gamma_{\rm total}$ Γ_{98}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0070	90	[211] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[211] ALBRECHT 89G reports < 0.0078 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^0 \gamma)/\Gamma_{\rm total}$ Γ_{99}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0043	90	[212] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[212] ALBRECHT 89G reports < 0.0048 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_2^*(1430)^0 \gamma)/\Gamma_{\rm total}$ Γ_{100}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.0 \times 10^{-4}$	90	[213] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[213] ALBRECHT 89G reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(1680)^0 \gamma)/\Gamma_{\rm total}$ Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0020	90	[214] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[214] ALBRECHT 89G reports < 0.0022 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_3^*(1780)^0\gamma)/\Gamma_{\rm total}$ Γ_{102}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.010	90	[215] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[215] ALBRECHT 89G reports < 0.011 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_4^*(2045)^0\gamma)/\Gamma_{\rm total}$ Γ_{103}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0043	90	[216] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

[216] ALBRECHT 89G reports < 0.0048 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\phi\phi)/\Gamma_{\rm total}$ Γ_{104}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{105}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.5 \times 10^{-5}$	90		GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.5 \times 10^{-5}$	90		[217] ADAM 96D	DLPH	$e^+e^- \to Z$
$<2.0 \times 10^{-5}$	90		ASNER 96	CLE2	Repl. by GODANG 98
$<4.1 \times 10^{-5}$	90		[218] BUSKULIC 96V	ALEP	$e^+e^- \to Z$
$<5.5 \times 10^{-5}$	90		[219] ABREU 95N	DLPH	Sup. by ADAM 96D
$<4.7 \times 10^{-5}$	90		[220] AKERS 94L	OPAL	$e^+e^- \to Z$
$<2.9 \times 10^{-5}$	90		[221] BATTLE 93	CLE2	$e^+e^- \to \Upsilon(4S)$
$<1.3 \times 10^{-4}$	90		[221] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<7.7 \times 10^{-5}$	90		[222] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2.6 \times 10^{-4}$	90		[222] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<5 \times 10^{-4}$	90	4	GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[217] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[218] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[219] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[220] Assumes $B(Z \to b\overline{b}) = 0.217$ and B_d^0 (B_s^0) fraction 39.5% (12%).

[221] Assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[222] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_{106}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.3 \times 10^{-6}$	90	GODANG 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<0.91 \times 10^{-5}$	90	ASNER 96	CLE2	Repl. by GODANG 98
$<6.0 \times 10^{-5}$	90	[223] ACCIARRI 95H	L3	$e^+e^- \to Z$

[223] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\pi^0)/\Gamma_{\rm total}$ Γ_{107}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8 \times 10^{-6}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.5 \times 10^{-4}$	90	[224] ACCIARRI 95H	L3	$e^+e^- \to Z$
$<1.8 \times 10^{-3}$	90	[225] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[224] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

[225] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta\eta)/\Gamma_{\rm total}$ Γ_{108}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.8 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.1 \times 10^{-4}$	90	[226] ACCIARRI 95H	L3	$e^+e^- \to Z$

[226] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta'\pi^0)/\Gamma_{\rm total}$ Γ_{109}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta'\eta')/\Gamma_{\rm total}$ Γ_{110}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.7 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta'\eta)/\Gamma_{\rm total}$ Γ_{111}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.7 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta'\rho^0)/\Gamma_{\rm total}$ Γ_{112}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.3 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\eta\rho^0)/\Gamma_{\rm total}$ Γ_{113}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3 \times 10^{-5}$	90	BEHRENS 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_{114}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7.2 \times 10^{-4}$	90	[227] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[227] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0\pi^0)/\Gamma_{\rm total}$ Γ_{115}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.4 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.0 \times 10^{-4}$	90	[228] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[228] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^\mp\pi^\pm)/\Gamma_{\rm total}$ Γ_{116}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.8 \times 10^{-5}$	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.2 \times 10^{-4}$	90	[229] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<5.2 \times 10^{-3}$	90	[230] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[229] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[230] BEBEK 87 reports $< 6.1 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{117}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.3 \times 10^{-4}$	90	[231] ADAM 96D	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.8 \times 10^{-4}$	90	[232] ABREU 95N	DLPH	Sup. by ADAM 96D
$<6.7 \times 10^{-4}$	90	[233] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[231] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[232] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[233] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0\rho^0)/\Gamma_{\rm total}$ Γ_{118}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-4}$	90	[234] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.9 \times 10^{-4}$	90	[235] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
$<4.3 \times 10^{-4}$	90	[235] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[234] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[235] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(a_1(1260)^\mp\pi^\pm)/\Gamma_{\rm total}$ Γ_{119}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.9 \times 10^{-4}$	90	[236] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.3 \times 10^{-4}$	90	[237] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.0 \times 10^{-3}$	90	[236] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[236] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[237] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_2(1320)^\mp\pi^\pm)/\Gamma_{\rm total}$ Γ_{120}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-4}$	90	[238] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.4 \times 10^{-3}$	90	[238] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[238] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_{121}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.1 \times 10^{-3}$	90	[239] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[239] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\rho^-)/\Gamma_{\rm total}$ Γ_{122}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.2 \times 10^{-3}$	90	[240] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[240] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\pi^0)/\Gamma_{\rm total}$ Γ_{123}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-3}$	90	[241] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[241] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\omega\pi^0)/\Gamma_{\rm total}$ Γ_{124}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.6 \times 10^{-4}$	90	[242] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[242] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{125}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9.0 \times 10^{-3}$	90	[243] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[243] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+\rho^-)/\Gamma_{\text{total}}$ Γ_{126}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.4 \times 10^{-3}$	90	[244] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[244] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\rho^0)/\Gamma_{\text{total}}$ Γ_{127}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.4 \times 10^{-3}$	90	[245] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[245] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_{128}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	[246] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[246] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+a_1(1260)^-)/\Gamma_{\text{total}}$ Γ_{129}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-3}$	90	[247] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<6.0 \times 10^{-3}$	90	[248] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[247] BORTOLETTO 89 reports $< 3.2 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[248] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{130}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-2}$	90	[249] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[249] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_{131}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.8 \times 10^{-5}$	90	[250] BUSKULIC 96V	ALEP	$e^+e^- \to Z$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<3.5 \times 10^{-4}$	90	[251] ABREU 95N	DLPH	Sup. by ADAM 96D
$<3.4 \times 10^{-5}$	90	[252] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$
$<1.2 \times 10^{-4}$	90	[253] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$
$<1.7 \times 10^{-4}$	90	[252] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[250] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[251] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[252] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[253] ALBRECHT 88F reports $< 1.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{132}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<2.5	90	[254] BEBEK 89	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

<9.5	90	[255] ABREU 95N	DLPH	Sup. by ADAM 96D
$5.4 \pm 1.8 \pm 2.0$		[256] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[254] BEBEK 89 reports $< 2.9 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[255] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[256] ALBRECHT 88F reports $6.0 \pm 2.0 \pm 2.2$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{\Lambda}\pi^-)/\Gamma_{\text{total}}$ Γ_{133}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.8 \times 10^{-4}$	90	[257] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[257] ALBRECHT 88F reports $< 2.0 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^0\overline{\Delta}^0)/\Gamma_{\text{total}}$ Γ_{134}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0015	90	[258] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[258] BORTOLETTO 89 reports < 0.0018 assuming $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^{++}\Delta^{--})/\Gamma_{\text{total}}$ Γ_{135}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-4}$	90	[259] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[259] BORTOLETTO 89 reports $< 1.3 \times 10^{-4}$ assuming $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\overline{\Sigma}_c^{--}\Delta^{++})/\Gamma_{\text{total}}$ Γ_{136}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0010	90	[260] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[260] PROCARIO 94 reports < 0.0012 for $B(\Lambda_c^+ \to pK^-\pi^+) = 0.043$. We rescale to our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.050$.

$\Gamma(\Lambda_c^- p\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{137}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$1.33^{+0.46}_{-0.42} \pm 0.37$	[261] FU 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[261] FU 97 uses PDG 96 values of Λ_c branching fraction.

$\Gamma(\Lambda_c^- p)/\Gamma_{\text{total}}$ Γ_{138}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.1 \times 10^{-4}$	90	[262] FU 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[262] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\Lambda_c^- p\pi^0)/\Gamma_{\text{total}}$ Γ_{139}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.9 \times 10^{-4}$	90	[263] FU 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[263] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\Lambda_c^- p\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{140}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.07 \times 10^{-3}$	90	[264] FU 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[264] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\Lambda_c^- p\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{141}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.74 \times 10^{-3}$	90	[265] FU 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[265] FU 97 uses PDG 96 values of Λ_c branching ratio.

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{142}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-5}$	90	[266] ACCIARRI 95I	L3	$e^+e^- \to Z$

[266] ACCIARRI 95I assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{143}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.9 \times 10^{-6}$	90	AMMAR 94	CLE2	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<1.4 \times 10^{-5}$	90	[267] ACCIARRI 97B	L3	$e^+e^- \to Z$
$<2.6 \times 10^{-5}$	90	[268] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<7.6 \times 10^{-5}$	90	[269] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
$<6.4 \times 10^{-5}$	90	[270] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<3 \times 10^{-4}$	90	GILES 84	CLEO	Repl. by AVERY 87

[267] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.

[268] AVERY 89B reports $< 3 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[269] ALBRECHT 87D reports $< 8.5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

[270] AVERY 87 reports $< 8 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{144}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.8 \times 10^{-7}$	90	[271] ABE 98	CDF	$p\overline{p}$ at 1.8 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$<4.0 \times 10^{-5}$	90	ABBOTT 98B	D0	$p\overline{p}$ 1.8 TeV
$<1.0 \times 10^{-5}$	90	[272] ACCIARRI 97B	L3	$e^+e^- \to Z$
$<1.6 \times 10^{-6}$	90	[273] ABE 96L	CDF	Repl. by ABE 98
$<5.9 \times 10^{-6}$	90	AMMAR 94	CLE2	$e^+e^- \to \Upsilon(4S)$
$<8.3 \times 10^{-6}$	90	[274] ALBAJAR 91C	UA1	$E_{\text{cm}}^{p\overline{p}} = 630$ GeV
$<1.2 \times 10^{-5}$	90	[275] ALBAJAR 91C	UA1	$E_{\text{cm}}^{p\overline{p}} = 630$ GeV
$<4.3 \times 10^{-5}$	90	[276] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<4.5 \times 10^{-5}$	90	[277] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
$<7.7 \times 10^{-5}$	90	[278] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2 \times 10^{-4}$	90	GILES 84	CLEO	Repl. by AVERY 87

[271] ABE 98 assumes production of $\sigma(B^0) = \sigma(B^+)$ and $\sigma(B_s)/\sigma(B^0) = 1/3$. They normalize to their measured $\sigma(B^0, p_T(B) > 6, |y| < 1.0) = 2.39 \pm 0.32 \pm 0.44\ \mu$b.

[272] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.

[273] ABE 96L assumes equal B^0 and B^+ production. They normalize to their measured $\sigma(B^+, p_T(B) > 6$ GeV/c, $|y| < 1) = 2.39 \pm 0.54\ \mu$b.

[274] B^0 and B_s^0 are not separated.

[275] Obtained from unseparated B^0 and B_s^0 measurement by assuming a B^0:B_s^0 ratio 2:1.

[276] AVERY 89B reports $< 5 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$. We rescale to 50%.
[277] ALBRECHT 87D reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0 \overline{B}^0$. We rescale to 50%.
[278] AVERY 87 reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0 \overline{B}^0$. We rescale to 50%.

$\Gamma(K^0 e^+ e^-)/\Gamma_{\text{total}}$ Γ_{145}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.0 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.2 \times 10^{-4}$	90	[279] AVERY	87	CLEO	$e^+ e^- \rightarrow \Upsilon(4S)$

[279] AVERY 87 reports $< 6.5 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0 \overline{B}^0$. We rescale to 50%.

$\Gamma(K^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{146}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.6 \times 10^{-4}$	90	[280] AVERY	87	CLEO	$e^+ e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.2 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$

[280] AVERY 87 reports $< 4.5 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0 \overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0 e^+ e^-)/\Gamma_{\text{total}}$ Γ_{147}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.9 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^*(892)^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_{148}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.3 \times 10^{-5}$	90	[281] ALBAJAR	91C	UA1	$E^{p\overline{p}}_{\text{cm}} = 630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.5 \times 10^{-5}$	90	[282] ABE	96L	CDF	$p\overline{p}$ at 1.8 TeV
$<3.4 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$

[281] ALBAJAR 91C assumes 36% of $\overline{b}$ quarks give B^0 mesons.
[282] ABE 96L measured relative to $B^0 \rightarrow J/\psi(1S) K^*(892)^0$ using PDG 94 branching ratios.

$\Gamma(K^*(892)^0 \nu \overline{\nu})/\Gamma_{\text{total}}$ Γ_{149}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[283] ADAM	96D	DLPH	$e^+ e^- \rightarrow Z$

[283] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

$\Gamma(e^{\pm} \mu^{\mp})/\Gamma_{\text{total}}$ Γ_{150}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5.9 \times 10^{-6}$	90	AMMAR	94	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.6 \times 10^{-5}$	90	[284] ACCIARRI	97B	L3	$e^+ e^- \rightarrow Z$
$<3.4 \times 10^{-5}$	90	[285] AVERY	89B	CLEO	$e^+ e^- \rightarrow \Upsilon(4S)$
$<4.5 \times 10^{-5}$	90	[286] ALBRECHT	87D	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$
$<7.7 \times 10^{-5}$	90	[287] AVERY	87	CLEO	$e^+ e^- \rightarrow \Upsilon(4S)$
$<3 \times 10^{-4}$	90	GILES	84	CLEO	Repl. by AVERY 87

[284] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.
[285] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$. We rescale to 50%.
[286] ALBRECHT 87D reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0 \overline{B}^0$. We rescale to 50%.
[287] AVERY 87 reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0 \overline{B}^0$. We rescale to 50%.

$\Gamma(e^{\pm} \tau^{\mp})/\Gamma_{\text{total}}$ Γ_{151}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5.3 \times 10^{-4}$	90	AMMAR	94	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$

$\Gamma(\mu^{\pm} \tau^{\mp})/\Gamma_{\text{total}}$ Γ_{152}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.3 \times 10^{-4}$	90	AMMAR	94	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$

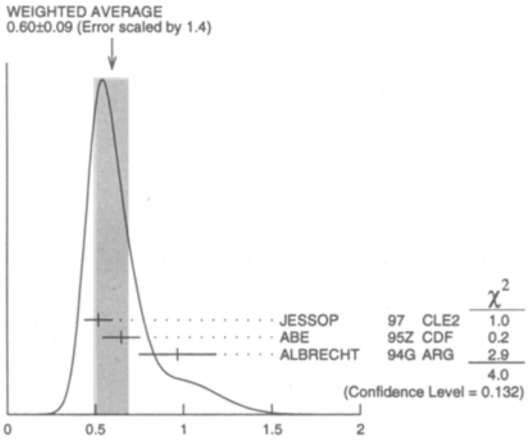
POLARIZATION IN B^0 DECAY

Γ_L/Γ in $B^0 \rightarrow J/\psi(1S) K^*(892)^0$

$\Gamma_L/\Gamma = 1[0]$ would indicate that $B^0 \rightarrow J/\psi(1S) K^*(892)^0$ followed by $K^*(892)^0 \rightarrow K^0_S \pi^0$ is a pure CP eigenstate with $CP = -1[+1]$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.60±0.09 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
0.52±0.07±0.04		[288] JESSOP	97	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$
0.65±0.10±0.04	65	ABE	95Z	CDF	$p\overline{p}$ at 1.8 TeV
0.97±0.16±0.15	13	[289] ALBRECHT	94G	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.80±0.08±0.05	42	[289] ALAM	94	CLE2	Sup. by JESSOP 97

[288] JESSOP 97 is the average over a mixture of B^0 and B^+ decays. The P-wave fraction is found to be 0.16 ± 0.08 ± 0.04.
[289] Averaged over an admixture of B^0 and B^+ decays.



Γ_L/Γ in $B^0 \rightarrow J/\psi(1S) K^*(892)^0$

Γ_L/Γ in $B^0 \rightarrow D^{*-} \rho^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.93±0.05±0.05	76	ALAM	94	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$

B^0–$\overline{B}^0$ MIXING

Revised December 1997 by H. Quinn (SLAC)

There are two neutral B meson systems which are like the neutral kaon system, in that two CP-conjugate states exist: the states $B^0 = \overline{b}d$, and $\overline{B}^0 = \overline{d}b$, which we will call the B_d system; and the states $B^0_s = \overline{b}s$, and $\overline{B}^0_s = \overline{s}b$, which we call the B_s system. For early work on CP violation in the B systems, chiefly the B_d system, see Ref. 1. In both these systems the mass eigenstates are not CP eigenstates, but are mixtures of the two CP-conjugate quark states. The fact that the mixing, due to box diagrams, shown in Fig. 1, produces non-CP eigenstates means that there is a CP-violating phase that enters in the amplitude for these diagrams. The two mass eigenstates can be written, for example for the B_d system,

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \ ,$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle \ . \tag{1}$$

Here H and L stand for Heavy and Light, respectively.

The complex coefficients p and q obey the normalization condition

$$|q|^2 + |p|^2 = 1 \ . \tag{2}$$

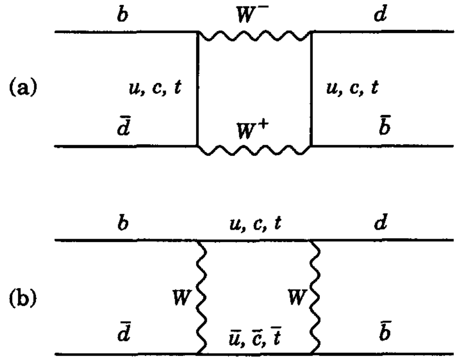


Figure 1: Mixing Diagrams.

We define the mass difference ΔM and width difference $\Delta\Gamma$ between the neutral B mesons:

$$\Delta M \equiv M_H - M_L \ ,$$
$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L \ , \qquad (3)$$

so that ΔM is positive by definition. Finding the eigenvalues of the mass-mixing matrix, one gets

$$(\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 - \frac{1}{4}|\Gamma_{12}|^2) \qquad (4)$$

and

$$\Delta M \Delta\Gamma = 4\mathrm{Re}\,(M_{12}\Gamma^*_{12}) \ , \qquad (5)$$

where the off-diagonal term of the mixing matrix is written as $M_{12} + i\Gamma_{12}$. Note that both M_{12} and Γ_{12} may be complex quantities; the separation is defined by the fact that Γ_{12} is given by the absorbtive part of the diagrams (cut contributions). The ratio q/p is given by

$$\frac{q}{p} = -\frac{\Delta M - \frac{i}{2}\Delta\Gamma}{2(M_{12} - \frac{i}{2}\Gamma_{12})} = -\frac{2(M^*_{12} - \frac{i}{2}\Gamma^*_{12})}{\Delta M - \frac{i}{2}\Delta\Gamma} \ . \qquad (6)$$

Whereas in the kaon case the lifetimes of the two eigenstates are significantly different and the difference in masses between them is small, in the B_d system it is the mass differences that dominate the physics, and the two states have nearly equal predicted widths (and thus lifetimes). We define, for $q = d, s$

$$x_q = \frac{\Delta M_q}{\Gamma_q} \ , \qquad y_q = \frac{\Delta\Gamma_q}{\Gamma_q} \ . \qquad (7)$$

The value of x_d is about 0.7, not very different from the similar quantity for the K^0 which is 0.48. The difference between the widths of the two B_d eigenstates is produced by the contributions from channels to which both B^0 and $\overline{B}^0$ can decay. These have branching ratios of $\mathcal{O}(10^{-3})$ [2]. Furthermore there are contributions of both signs to the difference, so there is no reason that the net effect should be much larger than the individual terms. Conservatively, one expects $y_d \leq 10^{-2}$and thus also $|q/p|_d$ equal to 1 to a very good approximation. Experimentally no effect of a difference in lifetimes has been observed.

For B_s there is currently only a lower bound on the value of x_s. Theoretical expectation is that it may be as large as 20 or more, which makes it quite difficult to measure. A significant difference in widths is possible, due to the fact that a number of the simplest two-body channels contribute only to a single CP (like the two-pion state which dominates K-decays and is the source of the large width difference in that system). The difference in widths could be as much as 20% of the total width in the B_s system [3]. Note that this still gives a small ratio, of order a few percent, for $\Delta\Gamma/\Delta M$.

The proper time evolution of an initially ($t = 0$) pure B^0 or $\overline{B}^0$ is given by

$$|B^0_{\rm phys}(t)\rangle = g_+(t)|B^0\rangle + (q/p)g_-(t)|\overline{B}^0\rangle \ ,$$
$$|\overline{B}^0_{\rm phys}(t)\rangle = (p/q)g_-(t)|B^0\rangle + g_+(t)|\overline{B}^0\rangle \ . \qquad (8)$$

where

$$g_\pm = \tfrac{1}{2}\exp(-\Gamma t/2)\exp(-iMt)$$
$$\times \left\{e^{-(\Delta\Gamma/2 - \Delta M)t} \pm e^{+(\Delta\Gamma/2 - \Delta M)t}\right\} \ . \qquad (9)$$

The rate at which an initial B^0_q ($\overline{B}^0_q$) decays as a $\overline{B}^0_q$ (B^0_q) is thus

$$R_q(t) = q/p \ (\mathrm{or}\ p/q)\Gamma|g_-(t)|^2 \ . \qquad (10)$$

The quantity χ_q measures the total probability that a created B^0 decays as a $\overline{B}^0$; it is given by

$$\chi_q = \int_0^\infty R_q(t)dt = \tfrac{1}{2}|q/p|^2 \frac{x_q^2 - y_q^2/4}{(1 + x_q^2)(1 - y_q^2/4)} \ , \qquad (11)$$

Time-dependent mixing measurements are now being done for the B_d system; earlier experiments measured only the time-integrated mixing, which is parameterized by a parameter χ_d. In this case to a good approximation we can set $|q/p| = 1$ and $|y_d| \ll x_d < 1$ so that the simpler form $\chi_d = \frac{1}{2}\frac{x_d^2}{1+x_d^2}$ applies, and a measurement of χ_d implies a value of x_d .

In the B^0–$\overline{B}^0$ mixing section of the B^0 Particle Listings, we list the χ_d measurements, most of which come from $\Upsilon(4S)$ data, and the Δm_{B^0} measurements, which come from Z data. We average these sections separately, but then include the results from both sections in "OUR EVALUATION" of χ_s and $\Delta M_{B^0_s}$. We convert both of these sets of measurements and list them in the x_d section. The x_d values obtained from Δm_{B^0} measurements have a common systematic error due to the error on τ_{B^0}. The averaging takes this common systematic error into account.

Because of the large value of x_s the quantity χ_s will be close to its upper limit of 0.5. This means that one cannot determine x_s accurately by measuring χ_s. It will require excellent time resolution to resolve the time-dependent mixing of the B^0_s system, and thereby determine $\Delta M_{B^0_s}$.

In the B^0_s–$\overline{B}^0_s$ mixing section of the B^0_s Particle Listings, we give measurements of χ_B, the mixing parameter for a high-energy admixture of b-hadrons

$$\chi_B = f_d \frac{\mathcal{B}_d}{\langle\mathcal{B}\rangle}\chi_d + f_s \frac{\mathcal{B}_s}{\langle\mathcal{B}\rangle}\chi_s \ . \qquad (12)$$

Here f_d and f_s are the fractions of b hadrons that are produced as B^0 and B_s^0 mesons respectively, and $\mathcal{B}_d$, $\mathcal{B}_s$, and $\langle\mathcal{B}\rangle$ are branching fractions for B_d, B_s, and the b-hadron admixture respectively decaying to the observed mode. If we assume that $\chi_s = 0.5$ and $\mathcal{B}_d/\langle\mathcal{B}\rangle = \mathcal{B}_s/\langle\mathcal{B}\rangle = 1$, Eq. (12) can be used to determine f_s as discussed in the note on "Production and Decay of b-Flavored Hadrons."

References

1. A.B. Carter and A.I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); Phys. Rev. **D23**, 1567 (1981); I.I. Bigi and A.I. Sanda Nucl. Phys. **B193**, 85 (1981) and Nucl. Phys. **B281**, 41 (1987).
2. I.I. Bigi, V.A. Khoze, N.G. Uraltsev, and A.I. Sanda, in *CP Violation*, ed. C. Jarlskog (World Scientific, Singapore, 1989), p. 175.
3. R. Aleksan, A. Le Yaouanc, L. Oliver, O. Pene and J.C. Raynall, Phys. Lett. **B316**, 567 (1993); M. Beneke, G. Buchalla, I. Dunietz, Phys. Rev. **D54**, 4419 (1996).

B^0-$\overline{B}^0$ MIXING PARAMETERS

For a discussion of B^0-$\overline{B}^0$ mixing see the note on "B^0-$\overline{B}^0$ Mixing" in the B^0 Particle Listings above.

χ_d is a measure of the time-integrated B^0-$\overline{B}^0$ mixing probability that a produced $B^0(\overline{B}^0)$ decays as a $\overline{B}^0(B^0)$. Mixing violates $\Delta B \neq 2$ rule.

$$\chi_d = \frac{x_d^2}{2(1+x_d^2)}$$

$$x_d = \frac{\Delta m_{B^0}}{\Gamma_{B^0}} = (m_{B_H^0} - m_{B_L^0})\,\tau_{B^0}\,,$$

where H, L stand for heavy and light states of two B^0 CP eigenstates and $\tau_{B^0} = \frac{1}{0.5(\Gamma_{B_H^0}+\Gamma_{B_L^0})}$.

χ_d

This B^0-$\overline{B}^0$ mixing parameter is the the probability (integrated over time) that a produced B^0 (or $\overline{B}^0$) decays as a $\overline{B}^0$ (or B^0), e.g. for inclusive lepton decays

$$\chi_d = \Gamma(B^0 \to \ell^- X \text{ (via } \overline{B}^0))/\Gamma(B^0 \to \ell^\pm X)$$
$$= \Gamma(\overline{B}^0 \to \ell^+ X \text{ (via } B^0))/\Gamma(\overline{B}^0 \to \ell^\pm X)$$

Where experiments have measured the parameter $r = \chi/(1-\chi)$, we have converted to χ. Mixing violates the $\Delta B \neq 2$ rule.

Note that the measurement of χ at energies higher than the $\Upsilon(4S)$ have not separated χ_d from χ_s where the subscripts indicate $B^0(\overline{b}d)$ or $B_s^0(\overline{b}s)$. They are listed in the B_s^0-$\overline{B}_s^0$ MIXING section.

The experiments at $\Upsilon(4S)$ make an assumption about the $B^0\overline{B}^0$ fraction and about the ratio of the $B^\pm$ and B^0 semileptonic branching ratios (usually that it equals one).

OUR EVALUATION, provided by the LEP B Oscillation Working Group, includes χ_d calculated from Δm_{B^0} and τ_{B^0}.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.172±0.010 OUR EVALUATION				
0.156±0.024 OUR AVERAGE				
0.16 ±0.04 ±0.04		[290] ALBRECHT 94	ARG	$e^+e^- \to \Upsilon(4S)$
0.149±0.023±0.022		[291] BARTELT 93	CLE2	$e^+e^- \to \Upsilon(4S)$
0.171±0.048		[292] ALBRECHT 92L	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20 ±0.13 ±0.12		[293] ALBRECHT 96D	ARG	$e^+e^- \to \Upsilon(4S)$
0.19 ±0.07 ±0.09		[294] ALBRECHT 96D	ARG	$e^+e^- \to \Upsilon(4S)$
0.24 ±0.12		[295] ELSEN 90	JADE	e^+e^- 35–44 GeV
$0.158^{+0.052}_{-0.059}$		ARTUSO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
0.17 ±0.05		[296] ALBRECHT 87I	ARG	$e^+e^- \to \Upsilon(4S)$
<0.19	90	[297] BEAN 87B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.27	90	[298] AVERY 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[290] ALBRECHT 94 reports r=0.194 ± 0.062 ± 0.054. We convert to χ for comparison. Uses tagged events (lepton + pion from D^*).

[291] BARTELT 93 analysis performed using tagged events (lepton+pion from D^*). Using dilepton events they obtain $0.157 \pm 0.016^{+0.033}_{-0.028}$.

[292] ALBRECHT 92L is a combined measurement employing several lepton-based techniques. It uses all previous ARGUS data in addition to new data and therefore supersedes ALBRECHT 87I. A value of $r = 20.6 \pm 7.0\%$ is directly measured. The value can be used to measure $x = \Delta M/\Gamma = 0.72 \pm 0.15$ for the B_d meson. Assumes $f_{+-}/f_0 = 1.0 \pm 0.05$ and uses $\tau_{B^\pm}/\tau_{B^0} = (0.95 \pm 0.14)\,(f_{+-}/f_0)$.

[293] Uses $D^{*+} K^\pm$ correlations.

[294] Uses $(D^{*+}\ell^-)\,K^\pm$ correlations.

[295] These experiments see a combination of B_s and B_d mesons.

[296] ALBRECHT 87I is inclusive measurement with like-sign dileptons, with tagged B decays plus leptons, and one fully reconstructed event. Measures r=0.21 ± 0.08. We convert to χ for comparison. Superseded by ALBRECHT 92L.

[297] BEAN 87B measured $r < 0.24$; we converted to χ.

[298] Same-sign dilepton events. Limit assumes semileptonic BR for B^+ and B^0 equal. If $B^0/B^\pm$ ratio <0.58, no limit exists. The limit was corrected in BEAN 87B from $r < 0.30$ to $r < 0.37$. We converted this limit to χ.

$\Delta m_{B^0} = m_{B_H^0} - m_{B_L^0}$

$\Delta m_{B_s^0}$ is a measure of 2π times the B^0-$\overline{B}^0$ oscillation frequency in time-dependent mixing experiments.

The second "OUR EVALUATION" (0.470 ± 0.019) is an average of the data listed below performed by the LEP B Oscillation Working Group as described in our review "Production and Decays of B-flavored Hadrons" in the $B^\pm$ Section of these Listings. The averaging procedure takes into account correlations between the measurements.

The first "OUR EVALUATION" (0.464 ± 0.018), also provided by the LEP B Oscillation Working Group, includes Δm_d calculated from χ_d measured at $\Upsilon(4S)$.

VALUE (10^{12} $\hbar$ s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.464±0.018 OUR EVALUATION				
0.470±0.019 OUR EVALUATION				
$0.471^{+0.078+0.033}_{-0.068-0.034}$		[299] ABE 98C	CDF	$p\overline{p}$ at 1.8 TeV
0.458±0.046±0.032		[300] ACCIARRI 98D	L3	$e^+e^- \to Z$
0.437±0.043±0.044		[301] ACCIARRI 98D	L3	$e^+e^- \to Z$
0.472±0.049±0.053		[302] ACCIARRI 98D	L3	$e^+e^- \to Z$
0.523±0.072±0.043		[303] ABREU 97N	DLPH	$e^+e^- \to Z$
0.493±0.042±0.027		[301] ABREU 97N	DLPH	$e^+e^- \to Z$
0.499±0.053±0.015		[304] ABREU 97N	DLPH	$e^+e^- \to Z$
0.480±0.040±0.051		[300] ABREU 97N	DLPH	$e^+e^- \to Z$
$0.444\pm0.029^{+0.020}_{-0.017}$		[301] ACKERSTAFF 97U	OPAL	$e^+e^- \to Z$
$0.430\pm0.043^{+0.028}_{-0.030}$		[300] ACKERSTAFF 97V	OPAL	$e^+e^- \to Z$
0.482±0.044±0.024		[305] BUSKULIC 97D	ALEP	$e^+e^- \to Z$
0.404±0.045±0.027		[301] BUSKULIC 97D	ALEP	$e^+e^- \to Z$
0.452±0.039±0.044		[300] BUSKULIC 97D	ALEP	$e^+e^- \to Z$
0.539±0.060±0.024		[306] ALEXANDER 96V	OPAL	$e^+e^- \to Z$
$0.567\pm0.089^{+0.029}_{-0.023}$		[307] ALEXANDER 96V	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.444±0.028±0.028		[308] ACCIARRI 98D	L3	$e^+e^- \to Z$
0.497±0.035		[309] ABREU 97N	DLPH	$e^+e^- \to Z$
$0.467\pm0.022^{+0.017}_{-0.015}$		[310] ACKERSTAFF 97V	OPAL	$e^+e^- \to Z$
0.446±0.032		[311] BUSKULIC 97D	ALEP	$e^+e^- \to Z$
$0.531^{+0.050}_{-0.046}\pm0.078$		[312] ABREU 96Q	DLPH	Sup. by ABREU 97N
$0.496^{+0.055}_{-0.051}\pm0.043$		[300] ACCIARRI 96E	L3	Repl. by ACCIARRI 98D
$0.548\pm0.050^{+0.023}_{-0.019}$		[313] ALEXANDER 96V	OPAL	$e^+e^- \to Z$
0.496±0.046		[314] AKERS 95J	OPAL	Repl. by ACKERSTAFF 97V
$0.462^{+0.040+0.052}_{-0.053-0.035}$		[300] AKERS 95J	OPAL	Repl. by ACKERSTAFF 97V
0.50 ±0.12 ±0.06		[303] ABREU 94M	DLPH	Sup. by ABREU 97N
0.508±0.075±0.025		[306] AKERS 94C	OPAL	Repl. by ALEXANDER 96V
0.57 ±0.11 ±0.02	153	[307] AKERS 94H	OPAL	Repl. by ALEXANDER 96V
$0.50\ ^{+0.07}_{-0.06}\ ^{+0.11}_{-0.10}$		[300] BUSKULIC 94B	ALEP	Sup. by BUSKULIC 97D
$0.52\ ^{+0.10}_{-0.11}\ ^{+0.04}_{-0.03}$		[307] BUSKULIC 93K	ALEP	Sup. by BUSKULIC 97D

[299] Uses π-B in the same side.

[300] Uses ℓ-ℓ.

[301] Uses ℓ-Q_{hem}.

[302] Uses ℓ-ℓ with impact parameters.

[303] Uses $D^{*\pm}$-Q_{hem}.

[304] Uses $\pi_s^\pm\,\ell$-Q_{hem}.

[305] Uses $D^{*\pm}$-ℓ/Q_{hem}.

[306] Uses $D^{*\pm}\,\ell$-Q_{hem}.

[307] Uses $D^{*\pm}$-ℓ.

[308] ACCIARRI 98D combines results from ℓ-ℓ, ℓ-Q_{hem}, and ℓ-ℓ with impact parameters.

[309] ABREU 97N combines results from $D^{*\pm}$-Q_{hem}, ℓ-Q_{hem}, $\pi_s^\pm\,\ell$-Q_{hem}, and ℓ-ℓ.

[310] ACKERSTAFF 97V combines results from ℓ-ℓ, ℓ-Q_{hem}, D^*-ℓ, and $D^{*\pm}$-Q_{hem}.

[311] BUSKULIC 97D combines results from $D^{*\pm}$-ℓ/Q_{hem}, ℓ-Q_{hem}, and ℓ-ℓ.

[312] ABREU 96Q analysis performed using lepton, kaon, and jet-charge tags.

[313] ALEXANDER 96V combines results from $D^{*\pm}$-ℓ and $D^{*\pm}\,\ell$-Q_{hem}.

[314] AKERS 95J combines results fromt charge measurement, $D^{*\pm}\,\ell$-Q_{hem} and ℓ-ℓ.

$x_d = \Delta m_{B^0}/\Gamma_{B^0}$

The second "OUR EVALUATION" (0.734 ± 0.035) is an average of the data listed in Δm_{B^0} section performed by the LEP B Oscillation Working Group as described in our review "Production and Decays of B-flavored Hadrons" in the $B^{\pm}$ Section of these Listings. The averaging procedure takes into account correlations between the measurements.

The first "OUR EVALUATION" (0.723 ± 0.032), also provided by the LEP B Oscillation Working Group, includes χ_d measured at $\Upsilon(4S)$.

VALUE	*DOCUMENT ID*
0.723±0.032 OUR EVALUATION	
0.734±0.035 OUR EVALUATION	

CP VIOLATION IN *B* DECAY – STANDARD MODEL PREDICTIONS

Revised February 1998 by H. Quinn (SLAC).

The study of CP violation in B decays [1] offers an opportunity to test whether the Standard Model mechanism for CP violation, due to the phase structure of the CKM matrix, is the only source of such effects [2]. The known CP-violation effects in K decays can be accommodated by this mechanism, but do not provide a critical test of it.

The Unitarity conditions (see our Section on "The Cabibbo-Kobayashi-Maskawa mixing matrix")

$$V_{uq}V_{ub}^* + V_{cq}V_{cb}^* + V_{tq}V_{tb}^* = 0 \ , \tag{1}$$

with $q = s$ or $q = d$ where V_{ij} is an element of the CKM matrix can be represented as triangles in the complex plane. The three interior angles of the $q = d$ triangle are labeled

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \ , \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \ ,$$
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \ . \tag{2}$$

In terms of the Wolfenstein parameters [3] we can also write

$$\tan\alpha = \frac{\eta}{\eta^2 - \rho(1-\rho)} \ , \quad \tan\beta = \frac{\eta}{1-\rho} \ ,$$
$$\tan\gamma = \frac{\eta}{\rho} \ . \tag{3}$$

Notice that the sign as well the magnitude of these angles is meaningful and can be measured.

A major aim of CP-violation studies of B decays is to make enough independent measurements of the sides and angles that the Unitarity triangle is overdetermined and thereby to check the validity of the Standard Model predictions that relate various measurements to aspects of this triangle. Constraints can be made on the basis of present data on the B-meson masses and lifetimes, on the ratio of charmless decays to decays with charm (V_{ub}/V_{cb}), and on ϵ [4] in K decays. These constraints have been discussed in many places in the literature; for a recent summary see Ref. 5. The range of allowed values depends on matrix element estimates, these are difficult to calculate hadronic physics effects. Improved methods to calculate such quantities, and understand the uncertainties in them, are needed to further sharpen tests of the Standard Model. Because of the uncertainties in these quantities, any given "Standard Model allowed range," for example for (ρ, η), cannot be interpreted as a statistically-based error range.

The phases in decay amplitudes which arise because of the phase in the CKM matrix, are called weak phases; the phases which arise from final state rescattering effects are referred to as strong phases. When one compares the amplitude for decay to a CP eigenstate to that for the related CP-conjugate process, the weak phase ϕ_i of each contribution changes sign, while the strong phase δ_i is unchanged:

$$\mathcal{A} = \Sigma_i \mathcal{A}_i e^{i(\delta_i+\phi_i)} \ , \ \overline{\mathcal{A}} = \Sigma_i \mathcal{A}_i e^{i(\delta_i-\phi_i)} \ . \tag{4}$$

Direct CP violation is a difference in the direct decay rate between $B \to f$ and $\overline{B} \to \overline{f}$ without any contribution from mixing effects. This requires $|\mathcal{A}| \neq |\overline{\mathcal{A}}|$, which occurs only if there is more than one term in the sum Eq. (4), and then only if the two terms have both different weak phases and different strong phases. A nonzero result for $\mathrm{Re}(\epsilon'/\epsilon)$ in K decay is a direct CP-violation effect. Direct CP violation can occur both in charged channels and in neutral channels in B decays [4].

In the Standard Model direct CP violation occurs because there are two major classes of diagrams that contribute to weak decays, tree diagrams, and penguin diagrams, examples of which are shown in Fig. 1. Tree diagrams are those in which the W does not reconnect to the quark line from which it was emitted. Penguin diagrams are loop diagrams in which the W is re absorbed on the same quark line, producing a net change of flavor, and a gluon (for a strong penguin) or a photon or Z (for an electroweak penguin) is emitted from the loop. There may be several different tree diagrams for a given process, namely W emission and decay, W decay, W exchange between the initial valence quarks, and/or valence quark-antiquark annihilation to produce the W. However all such contributions which enter a given transition do so with the same CKM (weak) phase. Direct CP violation occurs because of interference between tree diagrams and those penguin diagrams which have different weak phases than the trees. In channels where there are no tree contributions, direct CP violation can arise because of interference between different penguin contributions.

To calculate the size of expected CP-violation effects one begins from the relevant quark decay diagrams. We divide the amplitudes into two factors: a CKM factor given by the CKM-matrix elements that enter at each W vertex, and a Feynman amplitude from evaluating the remainder of the diagram. The Feynman amplitude of the penguin diagram is suppressed relative to tree diagrams by a factor of order $\alpha_s(m_b)/4\pi$. Firm predictions based on this argument for the strength of the CP-violating effects in particular exclusive charged B-decay channels are not possible because the relationship between the free-quark decay diagrams and the exclusive meson-decay amplitudes depends on operator matrix elements and thus estimates are model dependent. Furthermore one cannot reliably predict the strong phases that contribute to the asymmetry.

There is one interesting exception to this last statement that gives a possible way to find large direct CP-violation effects with known strong phase differences. This is any situation where two or more resonance channels contribute to the same final state

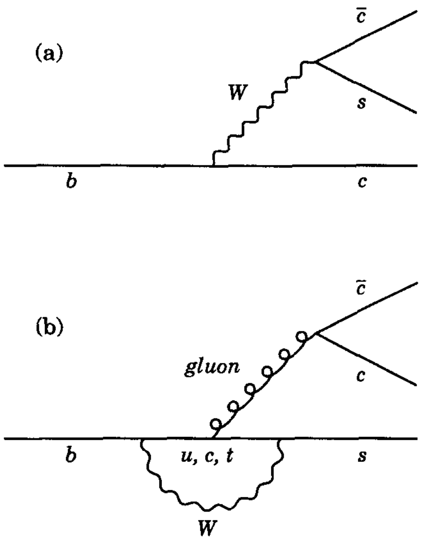


Figure 1: Quark level processes for $b \to c\overline{c}s$: (a) Tree diagram; (b) Penguin diagram. In the case of electroweak penguin contributions, the *gluon* is replaced by a Z or a γ.

set of particles in overlapping kinematic regions. The dominant contributions to the strong phases are then the resonant decay phases, which are known from measurements that determine the resonance mass and width. These give a known strong phase contribution which varies with the kinematics of the final particles and overlays the fixed strong phase of the resonance-production process. If two such resonant channels interfere, then there is a large and kinematically-varying known contribution to the strong phase difference between the contributions of the two channels. Examples include the interference of the different ρ-π charge combinations in the three pion final states [6] or interference between different $K^*\pi$ combinations in $K\pi\pi$ states. Detailed exploration of possible applications of these ideas can be found in Ref. 7.

A second type of CP violation, referred to as indirect CP violation, or CP violation in the mixing, would arise from any difference in the widths $\Delta\Gamma$ of the two mass eigenstates, or more precisely from complex mixing effects $\mathrm{Arg}(\Gamma_{12}M_{12}^*) \neq 0$, that would give $|q/p| \neq 1$ and also give a nonvanishing lifetime difference for the two B mass eigenstates [8]. Indirect CP violation in the K system is responsible for Re $\epsilon \neq 0$, which give CP-violating asymmetries in leptonic decay rates. Such effects are expected to be tiny in the B_d system, where both $|q/p| - 1$ and the difference of lifetimes $\Delta\Gamma/\Gamma$ are expected to be of order 10^{-2} [8]. For B_s a difference in the widths is possible, due to the fact that a number of the simplest two-body channels contribute only to a single CP. The difference in widths could be as much as 20% of the total width in the B_s system [9]. However the quantity $|q/p| - 1$ is expected to be even smaller in the B_s system than in the B_d system. An indirect CP-violating asymmetry would be seen as an charge asymmetry in the same-sign dilepton events produced via mixing from an incoherent state that initially contains a $B^0\overline{B}^0$ pair. This asymmetry vanishes with $\Delta\Gamma$; it is expected to be no larger than 1% in B_d decays [10].

There are additional CP-violating effects in neutral B decays which arise from interference between the two paths to a given final state f

$$B \to f \text{ or } B \to \overline{B} \to f \tag{5}$$

This effect, an interference between decay with and without mixing, is seen also in K decays where it contributes to the parameter Im ϵ. This interference can produce rate differences between B decay to a CP-eigenstate and the CP-conjugate $\overline{B}$ decay. Such asymmetries can be directly related to the CKM phases, provided there is no direct CP violation in addition to this effect. In channels where there is also direct CP violation, the relationship between the measured asymmetry and the CKM parameters is more complicated.

A simple way to distinguish the three types of CP violation is to note that direct CP violation occurs when $|\overline{\mathcal{A}}/\mathcal{A}| \neq 1$ while indirect CP violation requires $|q/p| \neq 1$ (see the review on B^0–$\overline{B}^0$ Mixing). CP violation due to the interference between direct decay and decay after mixing can occur when both quantities have unit absolute value; it requires only that their product have a nonzero weak phase [11].

Neutral B decays to CP eigenstates: The decays of neutral B mesons into CP eigenstates are of particular interest because many of these decays allow clean theoretical interpretation in terms of the parameters of the Standard Model [12]. We denote such a state by f_{CP}, for example $f_{CP} = J/\psi(1S)K_S$ or $f_{CP} = \pi\pi$, and define the amplitudes

$$\mathcal{A}_{f_{CP}} \equiv \langle f_{CP}|B^0\rangle\,, \quad \overline{\mathcal{A}}_{f_{CP}} \equiv \langle f_{CP}|\overline{B}^0\rangle \ . \tag{6}$$

For convenience let us introduce the quantity $\lambda_{f_{CP}}$

$$\lambda_{f_{CP}} \equiv \frac{q}{p}\,\frac{\overline{\mathcal{A}}_{f_{CP}}}{\mathcal{A}_{f_{CP}}} \ . \tag{7}$$

In the limit of no CP violation, $\lambda_{f_{CP}} = \pm 1$, where the sign is given by the CP eigenvalue of the particular state f_{CP}.

When the small difference in width of the two B_d states is ignored we can write

$$(q/p)_{B_d} = \frac{(V_{tb}^* V_{td})}{(V_{tb} V_{td}^*)} = e^{-2i\phi_M} \ , \tag{8}$$

where $2\phi_M$ denotes the CKM phase of the B–$\overline{B}$ mixing diagram (see the review on B^0–$\overline{B}^0$ Mixing). The time-dependent decay width for an initial $B^0(\overline{B}^0)$ state to decay to a state f is then given by

$$\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) =$$
$$|\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\left[\frac{1 + |\lambda_{f_{CP}}|^2}{2} + \frac{1 - |\lambda_{f_{CP}}|^2}{2}\right.$$
$$\left.\times \cos(\Delta M t) - \mathrm{Im}\ \lambda_{f_{CP}} \sin(\Delta M t)\right],$$

$$\Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP}) = |\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\left[\frac{1+|\lambda_{f_{CP}}|^2}{2} - \frac{1-|\lambda_{f_{CP}}|^2}{2} \times \cos(\Delta M t) + {\rm Im}\,\lambda_{f_{CP}} \sin(\Delta M t)\right] . \qquad (9)$$

The time-dependent CP asymmetry is thus

$$a_{f_{CP}}(t) \equiv \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})} = \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta M t) - 2{\rm Im}\,(\lambda_{f_{CP}})\sin(\Delta M t)}{1+|\lambda_{f_{CP}}|^2} . \qquad (10)$$

Further, when there is no direct CP violation in a channel, that is when all amplitudes that contribute have the same CKM decay-phase, ϕ_D, then $|\mathcal{A}_{f_{CP}}/\overline{\mathcal{A}}_{f_{CP}}| = 1$. In that case $\lambda_{f_{CP}}$ depends on CKM-matrix parameters only, without hadronic uncertainties, and can be written $\lambda_{f_{CP}} = \pm e^{-2i(\phi_D+\phi_M)}$. Then Eq. (10) simplifies to

$$a_{f_{CP}}(t) = \mp{\rm Im}\,(\lambda_{f_{CP}})\sin(\Delta M t) = \pm\sin(2(\phi_M+\phi_D))\sin(\Delta M t) . \qquad (11)$$

where the overall sign is given by the CP eigenvalue, ±1, of the final state f_{CP}. The mixing phase ϕ_M and the decay phase ϕ_D are each convention dependent, that is their value can be changed by redefining the phases of some of the quark fields. However Im $\lambda_{f_{CP}}$ depends on convention-independent combinations of CKM parameters only. From Eq. (11) one can directly relate the measured CP-violating asymmetry to the phase of particular combination of CKM-matrix elements in the Standard Model.

Extracting CKM parameters from measured asymmetries: In order make this relationship one looks at the CKM elements that appear in the relevant decay amplitudes and in the mixing diagrams. If the final state of the decay includes a K_S, an additional contribution from the K-mixing phase must be included in relating the measured asymmetry to the CKM parameters.

Whenever a penguin amplitude can contribute there are three separate diagrams, corresponding to the three flavors of up-type quarks in the loop. Each of these has a different CKM coefficient. We use the Unitarity condition Eq. (1) to express one coefficient as minus the sum of the other two. This regroups the three terms as a sum of two terms each of which involves a difference of two penguin diagrams (and thus is an ultra-violet finite quantity). As we will see below, the most convenient regrouping is different for $b \to q\overline{q}s$ decays and for $b \to q\overline{q}d$ decays.

When there is a tree diagram one of the two penguin terms will have the same CKM coefficient (and hence the same weak phase) as the tree diagram. Terms with the same weak phase can always be treated as a single contribution, from the perspective of looking for CP violations, although one must be sure to include all the relevant operators when estimating the expected size of such a term. In what follows we use the term "tree-dominated contribution" to describe a tree contribution plus any penguin contribution with the same weak phase. We label the second penguin term, which has a different CKM coefficient from the tree diagram as a "pure penguin contribution." Where no tree diagrams contribute there are two pure penguin terms. With this convention there are at most two terms with different weak decay phases that contribute for any decay in the Standard Model. It is instructive to note that any beyond-Standard-Model contribution, whatever its weak phase, can always be written as a sum of two terms with the weak phases of the two Standard Model terms, thus it is the pattern of relative strengths, and isospin structure, of the two terms that is peculiar to the Standard Model. (Care should be taken when comparing the terms defined by this grouping with statements in the literature about the sizes of terms made using definitions that do not include this regrouping.)

Table 1 gives the CKM factors for the various $b \to q\overline{q}'s$-quark decay channels. Here we choose to group penguin terms by eliminating the coefficient $V_{ts}V^*_{tb}$. Note that the two penguin terms in this arrangement are each the difference between a top quark contribution and a lighter (c or u) quark contribution, so they differ only by the mass dependent factors in this second

Table 1: $B \to q\overline{q}s$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\overline{c}s$	$V_{cb}V^*_{cs} = A\lambda^2$ tree + penguin$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	$J/\psi\ K_S$	β	$\psi\eta$ $D_s\overline{D}_s$	0
$b \to s\overline{s}s$	$V_{cb}V^*_{cs} = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	ϕK_S	β	$\phi\eta'$	0
$b \to u\overline{u}s$ $b \to d\overline{d}s$	$V_{cb}V^*_{cs} = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ tree + penguin$(u-t)$	$\pi^0\ K_S$ ρK_S	competing terms	$\phi\pi^0$ $K_S\overline{K}_S$	competing terms

contribution and by their overall sign and the CKM factors. One is suppressed by the CKM factor $\lambda^2(\rho - i\eta)$ compared to the other.

The columns labeled "Sample B_d Modes" and "Sample B_s Modes" list some of the simplest CP-study modes for each case. (These are either CP eigenstates, or modes from which CP-eigenstate contributions can be isolated, for example by angular analysis.) The columns labeled "Angle" show the angle of the unitarity triangle measured by $\phi_M + \phi_D$ where ϕ_M is the weak phase due to mixing, and ϕ_D that of the dominant decay amplitude (only the sum of these quantities is convention independent). Any Cabibbo-suppressed pure-penguin terms gives a negligible correction to this result. For the decay $b \to s\bar{s}s$ there is no tree contribution so the angle given is that due to the dominant penguin term, ignoring the Cabibbo-suppressed penguin term.

The quark decays to $u\bar{u}s$ and $d\bar{d}s$ contribute to the same set of final state hadrons and so must be combined. Here the tree diagram contributes to the Cabibbo-suppressed amplitude, so that the net result is that the two terms are expected to give comparable contributions with different CKM phases. For these decays, as with other direct CP-violating processes, there is no simple relationship between the measured asymmetry and a CKM phase, and thus no entry in the "Angle" columns in Table 1.

In addition to the neutral CP-eigenstate methods to determine the angles of the unitarity triangle listed in the tables, there are a number of other methods that involve decays that self-tag B-flavor, such as $DK^*(892)$ in either neutral [13] or charged [14] B decays. Further methods to measure γ in charged $B \to DK$ or $B \to D\pi$ have been suggested [15], which use interferences between a suppressed B decay followed by an allowed D decay and an allowed B decay followed by a suppressed D decay. However the relationship between the decay asymmetry and the angle is not as simple as Eq. (11) in this case. These methods require accurate measurements of several branching ratios, including a number that are quite small.

In Table 2 we list decays $b \to q\bar{q}'d$ decays. Here we choose to eliminate whichever of the two terms $V_{ud}V_{ub}^*$ or $V_{cd}V_{cb}^*$ is not present in the tree diagrams, so that the two penguin terms are one with the same weak phase as the tree and a second with CKM coefficient $V_{td}V_{tb}^*$ which has the opposite weak phase as the dominant mixing term in the Standard Model and hence a known value, zero, for $\phi_M + \phi_D$.

Here the competition between the tree-dominated and pure-penguin amplitudes is stronger because there is no Cabibbo suppression of the latter. The pure-penguin contributions are expected to be somewhat smaller because of the $\alpha(m_b)/\pi$ suppression factor. Table 2 lists the angle $\phi_M + \phi_D$, using ϕ_D for the tree-dominated terms as the angle measured. However the measured angle may be significantly shifted from this value if the pure-penguin terms turn out to be large. In certain cases one still may be able to extract a measurement of an angle, for example of $\sin(2\alpha)$ from the $\pi^+\pi^-$ asymmetry by measuring the rates in several isospin-related channels and using a multiparameter fit to separate a tree-only contribution [16]. The impact of electroweak penguins, which will not be removed by this analysis [17] is quite small in this channel [18]. This isospin analysis requires measuring the decay rate for channel $\pi^0\pi^0$, which will be a challenge. For the $\rho\pi$ decays the restrictions due to isospin can again be used to make a multiparameter fit to the ρ-regions of the Dalitz plot for $\pi^+\pi^-\pi^0$ distribution [6]. The interference between different ρ-charge channels is significant and may provide sufficient information to allow the separation of tree-dominated and pure-penguin effects and thus extraction of the parameter α. Isospin analyses at the very least can be used to test whether the penguin contributions are indeed small enough to be neglected in the determination of α.

In the case $b \to s\bar{s}d$ there are no tree graph contributions. The phase of the dominant penguin contribution is such that, combined with mixing effects, it gives a zero asymmetry for B_d decays and an asymmetry proportional to β for B_s decays. However, Gérard and Hou [19] have pointed out that interference with the sub-dominant penguin terms, proportional to

Table 2: $B \to q\bar{q}d$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\bar{c}d$	$V_{cb}V_{cd}^* = -A\lambda^3$ tree + penguin$(c-u)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	D^+D^-	$^*\beta$	ψK_S	$^*\beta_s$
$b \to s\bar{s}d$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	$V_{cb}V_{cd}^* = A\lambda^3$ penguin only$(c-u)$	$\phi\pi$ $K_S\overline{K}_S$	competing terms	ϕK_S	competing terms
$b \to u\bar{u}d$ $b \to d\bar{d}d$	$V_{ub}V_{ud}^* = A\lambda^3(\rho-i\eta)$ tree + penguin$(u-c)$	$V_{tb}V_{td}^* = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-c)$	$\pi\pi$; $\pi\rho$ πa_1	$^*\alpha$	π^0K_S ρ^0K_S	competing terms
$b \to c\bar{u}d$	$V_{cb}V_{ud}^* = A\lambda^2$	0	$D^0\pi^0$, $D^0\rho^0$ ↳ CP eigenstate	β	D^0K_S ↳ CP eigenstate	0

*Leading terms only.

$V_{ub}V^*_{ud}$ can give significant direct CP-violation asymmetries for such channels. Fleischer [20] has estimated that this asymmetry is possibly as large as 50%. While the sub-dominant term in this case would vanish if the masses of the up quark and the charm quark were equal, these estimates, which are based on the actual quark mass values and extreme values of operator matrix elements estimated using models, cannot be excluded. Thus, contrary to some comments in the literature, observation of CP-violating asymmetries in channels such as $B_d \to \phi\pi^0$ or $K^0\overline{K}^0$ would not necessarily require beyond-Standard-Model effects to explain them.

The entry for $b \to c\overline{u}d$ where the D^0 decays to a CP eigenstate ignores the small effect of doubly-Cabibbo-suppressed D-decays [21]. In contrast, the last entry indicates that one can select modes reached only by doubly-Cabibbo-suppressed decays from $D^0\pi$ and observe their interference with unsuppressed decays to the same channel from $\overline{D}^0\pi$ states, and thereby obtain a measurement of gamma [22].

There are some decay channels which are common to the B^0 and $\overline{B}^0$ but which are not CP eigenstates. For example the channel $J/\psi(1S)K^*(892)$ where the $K^*(892) \to K_S\pi^0$, the final state is not a CP eigenstate because both even and odd relative angular momenta between the $J/\psi(1S)$ and the $K^*(892)$ are allowed. One can use angular analysis to separate the different CP final states and measure the asymmetry in each [23]. The method applies in many quasi-two-body decays, such as other vector-vector channels, or those with higher-spin particles in final states. The branching ratio to these channels may be significantly larger than the CP-eigenstate (vector-scalar or scalar-scalar) channels with the same quark content. Such angular analyses may therefore be important in achieving accurate values for the parameters α and β.

Additional ways to extract CKM parameters by relationships between rates for channels such as $\pi\pi$, πK that can be extracted using SU(3) invariance have received considerable attention in the literature [24]. While these relationships will be interesting to investigate, the uncertainties introduced by SU(3) corrections may be significant. The review by Buras [5] gives a good summary of these ideas.

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CP VIOLATION PARAMETERS

$|\mathrm{Re}(\epsilon_{B^0})|$

CP impurity in B^0_d system. It is obtained from $a_{\ell\ell}$, the charge asymmetry in like-sign dilepton events at the $\Upsilon(4S)$.

$$\mathrm{Re}(\epsilon_{B^0}) \simeq \frac{1}{4}a_{\ell\ell} = \frac{1}{4}\,\frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)}\,.$$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.002±0.007±0.003	[315] ACKERSTAFF 97U	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.045	[316] BARTELT 93	CLE2	$e^+e^- \to \Upsilon(4S)$

[315] ACKERSTAFF 97U assumes *CPT* and is based on measuring the charge asymmetry in a sample of B^0 decays defined by lepton and Q_{hem} tags. If *CPT* is not invoked, $\mathrm{Re}(\epsilon_B) = -0.006 \pm 0.010 \pm 0.006$ is found. The indirect *CPT* violation parameter is determined to $\mathrm{Im}(\delta B) = -0.020 \pm 0.016 \pm 0.006$.

[316] BARTELT 93 finds $a_{\ell\ell} = 0.031 \pm 0.096 \pm 0.032$ which corresponds to $|a_{\ell\ell}| < 0.18$, which yields the above $\mathrm{Re}(\epsilon_{B^0})$.

$B^0 \rightarrow D^{*-}\ell^+\nu_\ell$ FORM FACTORS

See the review "Semileptonic decays of *B* mesons" for the definition of these parameters.

R_1 (form factor ratio $\sim V/A_1$)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.18±0.30±0.12	DUBOSCQ	96	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

R_2 (form factor ratio $\sim A_2/A_1$)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.71±0.22±0.07	DUBOSCQ	96	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

$\rho^2_{A_1}$ (form factor slope)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.91±0.15±0.06	DUBOSCQ	96	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

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ABE 98C PRL 80 2057 F. Abe+ (CDF Collab.)
ACCIARRI 98D EPJ C (to be publ.) M. Acciarri+ (L3 Collab.)
CERN-EP/98-28
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GODANG 98 PRL 80 3456 R. Godang+ (CLEO Collab.)
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ABREU 97F ZPHY C74 19 +Adam, Adye, Agasi+ (DELPHI Collab.)
Also 97K ZPHY C75 579 erratum
ABREU 97N ZPHY C76 579 P. Abreu+ (DELPHI Collab.)
ACCIARRI 97B PL B391 474 M. Acciarri+ (L3 Collab.)
ACCIARRI 97C PL B391 481 M. Acciarri+ (L3 Collab.)
ACKERSTAFF 97G PL B395 128 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 97U ZPHY C76 401 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 97V ZPHY C76 417 K. Ackerstaff+ (OPAL Collab.)
ARTUSO 97 PL B399 321 M. Artuso+ (CLEO Collab.)
ASNER 97 PRL 79 799 D. Asner+ (CLEO Collab.)
ATHANAS 97 PRL 79 2208 M. Athanas+ (CLEO Collab.)
BUSKULIC 97 PL B395 373 D. Buskulic+ (ALEPH Collab.)
BUSKULIC 97D ZPHY C75 397 D. Buskulic+ (ALEPH Collab.)
FU 97 PRL 79 3125 X. Fu+ (CLEO Collab.)
JESSOP 97 PRL 79 4533 C.P. Jessop+ (CLEO Collab.)
ABE 96B PR D53 3496 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 96C PRL 76 4462 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96H PRL 76 2015 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 96L PRL 76 4675 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96Q PR D54 6596 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABREU 96P ZPHY C71 539 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 96Q ZPHY C72 17 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 96E PL B383 487 +Adriani, Aguilar-Benitez, Ahlen+ (L3 Collab.)
ADAM 96D ZPHY C72 207 W. Adam+ (DELPHI Collab.)
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DUBOSCQ 96 PRL 76 3898 +Fulton, Fujino, Gan+ (CLEO Collab.)
GIBAUT 96 PR D53 4734 +Kinoshita, Pomianowski, Barish+ (CLEO Collab.)
PDG 96 PR D54 1
ABE 95Z PRL 75 3068 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABREU 95N PL B357 255 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 95Q ZPHY C68 13 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 95H PL B363 127 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ACCIARRI 95I PL B363 137 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ADAM 95 ZPHY C68 363 +Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 95J ZPHY C66 555 +Alexander, Allison, Ametewee+ (OPAL Collab.)
AKERS 95T ZPHY C67 379 +Alexander, Allison, Ametewee+ (OPAL Collab.)
ALEXANDER 95 PL B341 435 +Bebek, Berkelman, Bloom+ (CLEO Collab.)
Also 95C PL B347 469 (erratum) Alexander, Bebek, Berkelman, Bloom+ (CLEO Collab.)
BARISH 95 PR D51 1014 +Chadha, Chan, Cowen+ (CLEO Collab.)
BUSKULIC 95N PL B359 236 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
ABE 94D PRL 72 3456 +Albrow, Amidei, Anway-Wiese, Apollinari (CDF Collab.)
ABREU 94M PL B338 409 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 94C PL B327 411 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94H PL B336 585 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94J PL B337 196 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94L PL B337 393 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
ALAM 94 PR D50 43 +Kim, Nemati, O'Neill, Severini+ (CLEO Collab.)
ALBRECHT 94 PL B324 249 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ALBRECHT 94G PL B340 217 +Hamacher, Hofmann, Kirchhoff, Mankel+ (ARGUS Collab.)
AMMAR 94 PR D49 5701 +Ball, Baringer, Bean, Besson, Coppage+ (CLEO Collab.)
ATHANAS 94 PRL 73 3503 +Brower, Masek, Paar, Gronberg+ (CLEO Collab.)
Also 95 PRL 74 3090 (erratum) Athanas, Brower, Masek, Paar+ (CLEO Collab.)
BUSKULIC 94B PL B322 441 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
PROCARIO 94 PRL 73 1306 +Balest, Cho, Daoudi, Ford+ (CLEO Collab.)
STONE 94 HEPSY 93-11
ABREU 93D ZPHY C57 181 +Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ABREU 93G PL B312 253 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACTON 93C PL B307 247 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBRECHT 93 ZPHY C57 533 +Ehrlichmann, Hamacher, Hofmann+ (ARGUS Collab.)
ALBRECHT 93E ZPHY C60 11 +Ehrlichmann, Hamacher, Hofmann+ (ARGUS Collab.)
ALEXANDER 93B PL B319 365 +Bebek, Berkelman, Bloom, Browder+ (CLEO Collab.)
AMMAR 93 PRL 71 674 +Ball, Baringer, Coppage, Copty+ (CLEO Collab.)
BARTELT 93 PRL 71 1680 +Csorna, Egyed, Jain, Sheldon+ (CLEO Collab.)
BATTLE 93 PRL 71 3922 +Ernst, Kroha, Kwon, Roberts+ (CLEO Collab.)
BEAN 93B PRL 70 2681 +Gronberg, Kutschke, Menary, Morrison+ (CLEO Collab.)
BUSKULIC 93D PL B307 194 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
Also 94H PL B325 537 (errata)
BUSKULIC 93K PL B313 498 +De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
SANGHERA 93 PR D47 791 +Skwarnicki, Stroynowski, Artuso, Goldberg+(CLEO Collab.)
ALBRECHT 92C PL B275 195 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92G ZPHY C54 1 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92L ZPHY C55 357 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain+ (CLEO Collab.)
HENDERSON 92 PR D45 2212 +Kinoshita, Pipkin, Procario+ (CLEO Collab.)
KRAMER 92 PL B279 181 +Palmer (HAMB, OSU)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91E PL B273 540 +Albrow, Allkofer, Ankoviak+ (UA1 Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90B ZPHY C48 553 +Bartels, Bieler, Bienlein, Bizzeti+ (Crystal Ball Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
ELSEN 90 ZPHY C46 349 +Allison, Ambrus, Barlow, Bartel+ (JADE Collab.)
ROSNER 90 PR D42 3732
WAGNER 90 PRL 64 1095 +Hinshaw, Ong, Snyder+ (Mark II Collab.)
ALBRECHT 89C PL B219 121 +Boeckmannn, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89J PL B229 175 +Glaser, Harder+ (ARGUS Collab.)
ALBRECHT 89L PL B232 554 +Glaeser, Harder, Krueger, Nippe, Oest+ (ARGUS Collab.)
ARTUSO 89 PRL 62 2233 +Bebek, Berkelman, Blucher+ (CLEO Collab.)
AVERILL 89 PR D39 123 +Blockus, Brabson+ (HRS Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BEBEK 89 PRL 62 8 +Berkelman, Blucher+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
BORTOLETTO 89B PRL 63 1667 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87J PL B197 452 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 86F PL B182 95 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
CHEN 85 PR D31 2386 +Goldberg, Horwitz, Jawahery+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
AVERY 84 PRL 53 1309 +Bebek, Berkelman, Cassel+ (CLEO Collab.)
GILES 84 PR D30 2279 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
BEHRENDS 83 PRL 50 881 +Chadwick, Chauveau, Ganci+ (CLEO Collab.)

$B^\pm/B^0$ ADMIXTURE

B DECAY MODES

The branching fraction measurements are for an admixture of *B* mesons at the $\Upsilon(4S)$. The values quoted assume that $B(\Upsilon(4S) \rightarrow B\overline{B}) = 100\%$.

For inclusive branching fractions, *e.g.*, $B \rightarrow D^\pm$ anything, the treatment of multiple *D*'s in the final state must be defined. One possiblity would be to count the number of events with one-or-more *D*'s and divide by the total number of *B*'s. Another possibility would be to count the total number of *D*'s and divide by the total number of *B*'s, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the *B* sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

$\overline{B}$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$B \rightarrow e^+\nu_e$ anything	[a]	(10.41±0.29) %	S=1.2
Γ_2	$B \rightarrow \overline{p}e^+\nu_e$ anything		< 1.6 × 10^{-3}	CL=90%
Γ_3	$B \rightarrow \mu^+\nu_\mu$ anything	[a]	(10.3 ±0.5) %	
Γ_4	$B \rightarrow \ell^+\nu_\ell$ anything	[a,b]	(10.45±0.21) %	
Γ_5	$B \rightarrow D^-\ell^+\nu_\ell$ anything	[b]	(2.7 ±0.8) %	
Γ_6	$B \rightarrow \overline{D}^0\ell^+\nu_\ell$ anything	[b]	(7.0 ±1.4) %	
Γ_7	$B \rightarrow D^{*-}\ell^+\nu_\ell$ anything			
Γ_8	$B \rightarrow D^{*0}\ell^+\nu_\ell$ anything			
Γ_9	$B \rightarrow \overline{D}^{**}\ell^+\nu_\ell$	[b,c]	(2.7 ±0.7) %	
Γ_{10}	$B \rightarrow \overline{D}_1(2420)\ell^+\nu_\ell$ anything		(7.4 ±1.6) × 10^{-3}	
Γ_{11}	$B \rightarrow D\pi\ell^+\nu_\ell$ anything + $D^*\pi\ell^+\nu_\ell$ anything		(2.3 ±0.4) %	
Γ_{12}	$B \rightarrow \overline{D}^*_2(2460)\ell^+\nu_\ell$ anything		< 6.5 × 10^{-3}	CL=95%

Γ_{13}	$B \to D^{*-}\pi^+\ell^+\nu_\ell$ anything		$(1.00\pm0.34)\%$	
Γ_{14}	$B \to D_s^-\ell^+\nu_\ell$ anything	[b]	$< 9 \times 10^{-3}$	CL=90%
Γ_{15}	$B \to D_s^-\ell^+\nu_\ell K^+$ anything	[b]	$< 6 \times 10^{-3}$	CL=90%
Γ_{16}	$B \to D_s^-\ell^+\nu_\ell K^0$ anything	[b]	$< 9 \times 10^{-3}$	CL=90%
Γ_{17}	$B \to \ell^+\nu_\ell$ noncharmed	[b]		
Γ_{18}	$B \to K^+\ell^+\nu_\ell$ anything	[b]	$(6.0 \pm 0.5)\%$	
Γ_{19}	$B \to K^-\ell^+\nu_\ell$ anything	[b]	$(10 \pm 4) \times 10^{-3}$	
Γ_{20}	$B \to K^0/\overline{K}^0\ell^+\nu_\ell$ anything	[b]	$(4.4 \pm 0.5)\%$	

D, D^*, or D_s modes

Γ_{21}	$B \to D^\pm$ anything		$(24.1 \pm 1.9)\%$	
Γ_{22}	$B \to D^0/\overline{D}^0$ anything		$(63.1 \pm 2.9)\%$	S=1.1
Γ_{23}	$B \to D^*(2010)^\pm$ anything		$(22.7 \pm 1.6)\%$	
Γ_{24}	$B \to D^*(2007)^0$ anything		$(26.0 \pm 2.7)\%$	
Γ_{25}	$B \to D_s^\pm$ anything	[d]	$(10.0 \pm 2.5)\%$	
Γ_{26}	$b \to c\overline{c}s$		$(22 \pm 4)\%$	
Γ_{27}	$B \to D_s D$, $D_s^* D$, $D_s D^*$, or $D_s^* D^*$	[d]	$(4.9 \pm 1.3)\%$	
Γ_{28}	$B \to D^*(2010)\gamma$		$< 1.1 \times 10^{-3}$	CL=90%
Γ_{29}	$B \to D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, $D_s^{*+}\rho^-$, $D_s^+\pi^0$, $D_s^{*+}\pi^0$, $D_s^+\eta$, $D_s^{*+}\eta$, $D_s^+\rho^0$, $D_s^{*+}\rho^0$, $D_s^+\omega$, $D_s^{*+}\omega$	[d]	$< 5 \times 10^{-4}$	CL=90%
Γ_{30}	$B \to D_{s1}(2536)^+$ anything		$< 9.5 \times 10^{-3}$	CL=90%

Charmonium modes

Γ_{31}	$B \to J/\psi(1S)$ anything		$(1.13\pm0.06)\%$	
Γ_{32}	$B \to J/\psi(1S)$ (direct) anything		$(8.0 \pm 0.8) \times 10^{-3}$	
Γ_{33}	$B \to \psi(2S)$ anything		$(3.5 \pm 0.5) \times 10^{-3}$	
Γ_{34}	$B \to \chi_{c1}(1P)$ anything		$(4.2 \pm 0.7) \times 10^{-3}$	
Γ_{35}	$B \to \chi_{c1}(1P)$ (direct) anything		$(3.7 \pm 0.7) \times 10^{-3}$	
Γ_{36}	$B \to \chi_{c2}(1P)$ anything		$< 3.8 \times 10^{-3}$	CL=90%
Γ_{37}	$B \to \eta_c(1S)$ anything		$< 9 \times 10^{-3}$	CL=90%

K or K^* modes

Γ_{38}	$B \to K^\pm$ anything	[d]	$(78.9 \pm 2.5)\%$	
Γ_{39}	$B \to K^+$ anything		$(66 \pm 5)\%$	
Γ_{40}	$B \to K^-$ anything		$(13 \pm 4)\%$	
Γ_{41}	$B \to K^0/\overline{K}^0$ anything	[d]	$(64 \pm 4)\%$	
Γ_{42}	$B \to K^*(892)^\pm$ anything		$(18 \pm 6)\%$	
Γ_{43}	$B \to K^*(892)^0/\overline{K}^*(892)^0$ anything	[d]	$(14.6 \pm 2.6)\%$	
Γ_{44}	$B \to K^*(892)\gamma$			
Γ_{45}	$B \to K_1(1400)\gamma$		$< 4.1 \times 10^{-4}$	CL=90%
Γ_{46}	$B \to K_2^*(1430)\gamma$		$< 8.3 \times 10^{-4}$	CL=90%
Γ_{47}	$B \to K_2(1770)\gamma$		$< 1.2 \times 10^{-3}$	CL=90%
Γ_{48}	$B \to K_3^*(1780)\gamma$		$< 3.0 \times 10^{-3}$	CL=90%
Γ_{49}	$B \to K_4^*(2045)\gamma$		$< 1.0 \times 10^{-3}$	CL=90%
Γ_{50}	$B \to \overline{b} \to \overline{s}\gamma$		$(2.3 \pm 0.7) \times 10^{-4}$	
Γ_{51}	$B \to \overline{b} \to \overline{s}$ gluon		$< 6.8\ \%$	CL=90%

Light unflavored meson modes

Γ_{52}	$B \to \pi^\pm$ anything	[d,e]	$(359 \pm 7)\%$	
Γ_{53}	$B \to \eta$ anything		$(17.6 \pm 1.6)\%$	
Γ_{54}	$B \to \rho^0$ anything		$(21 \pm 5)\%$	
Γ_{55}	$B \to \omega$ anything		$< 81\ \%$	CL=90%
Γ_{56}	$B \to \phi$ anything		$(3.5 \pm 0.7)\%$	S=1.8

Baryon modes

Γ_{57}	$B \to \Lambda_c^\pm$ anything		$(6.4 \pm 1.1)\%$	
Γ_{58}	$B \to \Lambda_c^+$ anything			
Γ_{59}	$B \to \Lambda_c^-$ anything			
Γ_{60}	$B \to \Lambda_c^- e^+$ anything		$< 3.2 \times 10^{-3}$	CL=90%
Γ_{61}	$B \to \Lambda_c^- p$ anything		$(3.6 \pm 0.7)\%$	
Γ_{62}	$B \to \Lambda_c^- p e^+ \nu_e$		$< 1.5 \times 10^{-3}$	CL=90%
Γ_{63}	$B \to \overline{\Sigma}_c^{--}$ anything		$(4.2 \pm 2.4) \times 10^{-3}$	
Γ_{64}	$B \to \overline{\Sigma}_c^-$ anything		$< 9.6 \times 10^{-3}$	CL=90%
Γ_{65}	$B \to \overline{\Sigma}_c^0$ anything		$(4.6 \pm 2.4) \times 10^{-3}$	
Γ_{66}	$B \to \overline{\Sigma}_c^0 N (N = p$ or $n)$		$< 1.5 \times 10^{-3}$	CL=90%
Γ_{67}	$B \to \Xi_c^0$ anything $\times$ B$(\Xi_c^0 \to \Xi^-\pi^+)$		$(1.4 \pm 0.5) \times 10^{-4}$	
Γ_{68}	$B \to \Xi_c^+$ anything $\times$ B$(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$		$(4.5\ {}^{+1.3}_{-1.2}) \times 10^{-4}$	
Γ_{69}	$B \to p/\overline{p}$ anything	[d]	$(8.0 \pm 0.4)\%$	
Γ_{70}	$B \to p/\overline{p}$ (direct) anything	[d]	$(5.5 \pm 0.5)\%$	
Γ_{71}	$B \to \Lambda/\overline{\Lambda}$ anything	[d]	$(4.0 \pm 0.5)\%$	
Γ_{72}	$B \to \Lambda$ anything			
Γ_{73}	$B \to \overline{\Lambda}$ anything			
Γ_{74}	$B \to \Xi^-/\overline{\Xi}^+$ anything	[d]	$(2.7 \pm 0.6) \times 10^{-3}$	
Γ_{75}	$B \to$ baryons anything		$(6.8 \pm 0.6)\%$	
Γ_{76}	$B \to p\overline{p}$ anything		$(2.47\pm0.23)\%$	
Γ_{77}	$B \to \Lambda\overline{p}/\overline{\Lambda}p$ anything	[d]	$(2.5 \pm 0.4)\%$	
Γ_{78}	$B \to \Lambda\overline{\Lambda}$ anything		$< 5 \times 10^{-3}$	CL=90%

Lepton Family number (LF) violating modes or $\Delta B = 1$ weak neutral current ($B1$) modes

Γ_{79}	$B \to e^+e^- s$	$B1$	$< 5.7 \times 10^{-5}$	CL=90%
Γ_{80}	$B \to \mu^+\mu^- s$	$B1$	$< 5.8 \times 10^{-5}$	CL=90%
Γ_{81}	$B \to e^\pm\mu^\mp s$	LF	$< 2.2 \times 10^{-5}$	CL=90%

[a] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[b] An ℓ indicates an e or a μ mode, not a sum over these modes.

[c] D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances.

[d] The value is for the sum of the charge states of particle/antiparticle states indicated.

[e] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

$B^\pm/B^0$ ADMIXTURE BRANCHING RATIOS

$\Gamma(\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_4/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
0.1045±0.0021 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.		
0.108 ±0.002 ±0.0056	[1] HENDERSON 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[1] HENDERSON 92 measurement employs e and μ. The systematic error contains 0.004 in quadrature from model dependence. The authors average a variation of the Isgur, Scora, Grinstein, and Wise model with that of the Altarelli-Cabibbo-Corbò-Maiani-Martinelli model for semileptonic decays to correct the acceptance.

$\Gamma(e^+\nu_e\text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
0.1041±0.0029 OUR AVERAGE	Error includes scale factor of 1.2.		
0.1049±0.0017±0.0043	[2] BARISH 96B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.097 ±0.005 ±0.004	[3] ALBRECHT 93H	ARG	$e^+e^- \to \Upsilon(4S)$
0.100 ±0.004 ±0.003	[4] YANAGISAWA 91	CSB2	$e^+e^- \to \Upsilon(4S)$
0.103 ±0.006 ±0.002	[5] ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.117 ±0.004 ±0.010	[6] WACHS 89	CBAL	Direct e at $\Upsilon(4S)$
0.120 ±0.007 ±0.005	CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.132 ±0.008 ±0.014	[7] KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$

[2] BARISH 96B analysis performed using tagged semileptonic decays of the B. This technique is almost model independent for the lepton branching ratio.

[3] ALBRECHT 93H analysis performed using tagged semileptonic decays of the B. This technique is almost model independent for the lepton branching ratio.

[4] YANAGISAWA 91 also measures an average semileptonic branching ratio at the $\Upsilon(5S)$ of 9.6–10.5% depending on assumptions about the relative production of different B meson species.

[5] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.099 ± 0.006 is obtained using ISGUR 89B.

[6] Using data above $p(e) = 2.4$ GeV, WACHS 89 determine $\sigma(B \to e\nu\text{up})/\sigma(B \to e\nu\text{charm}) < 0.065$ at 90% CL.

[7] Ratio $\sigma(b \to e\nu\text{up})/\sigma(b \to e\nu\text{charm}) < 0.055$ at CL = 90%.

$\Gamma(\mu^+\nu_\mu\text{anything})/\Gamma_{\text{total}}$ Γ_3/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
0.103±0.005 OUR AVERAGE			
0.100±0.006±0.002	[8] ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.108±0.006±0.01	CHEN 84	CLEO	Direct μ at $\Upsilon(4S)$
0.112±0.009±0.01	LEVMAN 84	CUSB	Direct μ at $\Upsilon(4S)$

[8] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.097 ± 0.006 is obtained using ISGUR 89B.

$\Gamma(\bar{p}e^+\nu_e\text{anything})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0016	90	ALBRECHT 90H	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(D^-\ell^+\nu_\ell\text{anything})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_5/Γ_4

$\ell = e$ or μ.

VALUE	DOCUMENT ID	TECN	COMMENT
0.26±0.07±0.04	[9] FULTON 91	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[9] FULTON 91 uses B($D^+ \rightarrow K^-\pi^+\pi^+$) = (9.1 ± 1.3 ± 0.4)% as measured by MARK III.

$\Gamma(\overline{D}^0\ell^+\nu_\ell\text{anything})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_6/Γ_4

$\ell = e$ or μ.

VALUE	DOCUMENT ID	TECN	COMMENT
0.67±0.09±0.10	[10] FULTON 91	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[10] FULTON 91 uses B($D^0 \rightarrow K^-\pi^+$) = (4.2 ± 0.4 ± 0.4)% as measured by MARK III.

$\Gamma(D^{*-}\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.6±0.3±0.1	[11] BARISH 95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[11] BARISH 95 use B($D^0 \rightarrow K^-\pi^+$) = (3.91 ± 0.08 ± 0.17)% and B($D^{*+} \rightarrow D^0\pi^+$) = (68.1 ± 1.0 ± 1.3)%.

$\Gamma(D^{*0}\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.6±0.6±0.1	[12] BARISH 95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[12] BARISH 95 use B($D^0 \rightarrow K^-\pi^+$) = (3.91 ± 0.08 ± 0.17)%, B($D^{*+} \rightarrow D^0\pi^+$) = (68.1 ± 1.0 ± 1.3)%, B($D^{*0} \rightarrow D^0\pi^0$) = (63.6 ± 2.3 ± 3.3)%.

$\Gamma(\overline{D}^{**}\ell^+\nu_\ell)/\Gamma_{\text{total}}$ Γ_9/Γ

D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances. $\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.027±0.005±0.005		63	[13] ALBRECHT 93	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.028	95		[14] BARISH 95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[13] ALBRECHT 93 assumes the GISW model to correct for unseen modes. Using the BHKT model, the result becomes 0.023 ± 0.006 ± 0.004. Assumes B($D^{*+} \rightarrow D^0\pi^+$) = 68.1%, B($D^0 \rightarrow K^-\pi^+$) = 3.65%, B($D^0 \rightarrow K^-\pi^+\pi^-\pi^+$) = 7.5%. We have taken their average e and μ value.

[14] BARISH 95 use B($D^0 \rightarrow K^-\pi^+$) = (3.91 ± 0.08 ± 0.17)%, assume all nonresonant channels are zero, and use GISW model for relative abundances of D^{**} states.

$\Gamma(\overline{D}_1(2420)\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0074±0.0016	[15] BUSKULIC 97B	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	[16] BUSKULIC 95B	ALEP	Repl. by BUSKULIC 97B

[15] BUSKULIC 97B assumes B($D_1(2420) \rightarrow D^*\pi$) = 1, B($D_1(2420) \rightarrow D^*\pi^{\pm}$) = 2/3, and B($b \rightarrow B$) = 0.378 ± 0.022.

[16] BUSKULIC 95B reports f_B × B($B \rightarrow \overline{D}_1(2420)^0\ell^+\nu_\ell$anything) × B($\overline{D}_1(2420)^0 \rightarrow \overline{D}^*(2010)^-\pi^+$) = (2.04 ± 0.58 ± 0.34)$10^{-3}$, where f_B is the production fraction for a single B charge state.

$[\Gamma(D\pi\ell^+\nu_\ell\text{anything}) + \Gamma(D^*\pi\ell^+\nu_\ell\text{anything})]/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0226±0.0029±0.0033	[17] BUSKULIC 97B	ALEP	$e^+e^- \rightarrow Z$

[17] BUSKULIC 97B assumes B($b \rightarrow B$) = 0.378 ± 0.022 and uses isospin invariance by assuming that all observed $D^0\pi^+$, $D^{*0}\pi^+$, $D^+\pi^-$, and $D^{*+}\pi^-$ are from D^{**} states. A correction has been applied to account for the production of B^0_s and Λ^0_b.

$\Gamma(\overline{D}^*_2(2460)\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0065	95	[18] BUSKULIC 97B	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen		[19] BUSKULIC 95B	ALEP	$e^+e^- \rightarrow Z$

[18] A revised number based on BUSKULIC 97B which assumes B($D^*_2(2460) \rightarrow D^*\pi^{\pm}$) = 0.20 and B($b \rightarrow B$) = 0.378 ± 0.022.

[19] BUSKULIC 95B reports f_B × B($B \rightarrow \overline{D}^*_2(2460)^0\ell^+\nu_\ell$anything) × B($\overline{D}^*_2(2460)^0 \rightarrow \overline{D}^*(2010)^-\pi^+$) $\leq 0.81 \times 10^{-3}$ at CL=95%, where f_B is the production fraction for a single B charge state.

$\Gamma(D^{*-}\pi^+\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_{13}/Γ

Includes resonant and nonresonant contributions.

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
10.0±2.7±2.1	[20] BUSKULIC 95B	ALEP	$e^+e^- \rightarrow Z$

[20] BUSKULIC 95B reports f_B × B($B \rightarrow \overline{D}^*(2010)^-\pi^+\ell^+\nu_\ell$anything) = (3.7 ± 1.0 ± 0.7)10^{-3}. Above value assumes f_B = 0.37 ± 0.03.

$\Gamma(D^-_s\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.009	90	[21] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[21] ALBRECHT 93E reports < 0.012 for B($D^+_s \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D^+_s \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(D^-_s\ell^+\nu_\ell K^+\text{anything})/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	[22] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[22] ALBRECHT 93E reports < 0.008 for B($D^+_s \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D^+_s \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(D^-_s\ell^+\nu_\ell K^0\text{anything})/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.009	90	[23] ALBRECHT 93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[23] ALBRECHT 93E reports < 0.012 for B($D^+_s \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D^+_s \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(\ell^+\nu_\ell\text{noncharmed})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_{17}/Γ_4

ℓ denotes e or μ, not the sum. These experiments measure this ratio in very limited momentum intervals.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
			[24] ALBRECHT 94C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
		107	[25] BARTELT 93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
		77	[26] ALBRECHT 91C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
		76	[27] FULTON 90	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		41	[28] ALBRECHT 90	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<0.04	90		[29] BEHRENDS 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<0.04	90		CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
<0.055	90		KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$

[24] ALBRECHT 94C find $\Gamma(b \rightarrow c)/\Gamma(b \rightarrow \text{all})$ = 0.99 ± 0.02 ± 0.04.

[25] BARTELT 93B (CLEO II) measures an excess of 107 ± 15 ± 11 leptons in the lepton momentum interval 2.3–2.6 GeV/c which is attributed to $b \rightarrow u\ell\nu_\ell$. This corresponds to a model-dependent partial branching ratio ΔB_{ub} between (1.15 ± 0.16 ± 0.15) × 10^{-4}, as evaluated using the KS model (KOERNER 88), and (1.54 ± 0.22 ± 0.20) × 10^{-4} using the ACCMM model (ARTUSO 93). The corresponding values of $|V_{ub}|/|V_{cb}|$ are 0.056 ± 0.006 and 0.076 ± 0.008, respectively.

[26] ALBRECHT 91C result supersedes ALBRECHT 90. Two events are fully reconstructed providing evidence for the $b \rightarrow u$ transition. Using the model of ALTARELLI 82, they obtain $|V_{ub}/V_{cb}|$ = 0.11 ± 0.012 from 77 leptons in the 2.3–2.6 GeV momentum range.

[27] FULTON 90 observe 76 ± 20 excess e and μ (lepton) events in the momentum interval p = 2.4–2.6 GeV signaling the presence of the $b \rightarrow u$ transition. The average branching ratio, (1.8 ± 0.4 ± 0.3) × 10^{-4}, corresponds to a model-dependent measurement of approximately $|V_{ub}/V_{cb}|$ = 0.1 using B($b \rightarrow c\ell\nu$) = 10.2 ± 0.2 ± 0.7%.

[28] ALBRECHT 90 observes 41 ± 10 excess e and μ (lepton) events in the momentum interval p = 2.3–2.6 GeV signaling the presence of the $b \rightarrow u$ transition. The events correspond to a model-dependent measurement of $|V_{ub}/V_{cb}|$ = 0.10 ± 0.01.

[29] The quoted possible limits range from 0.018 to 0.04 for the ratio, depending on which model or momentum range is chosen. We select the most conservative limit they have calculated. This corresponds to a limit on $|V_{ub}|/|V_{cb}| <$ 0.20. While the endpoint technique employed is more robust than their previous results in CHEN 84, these results do not provide a numerical improvement in the limit.

$\Gamma(K^+\ell^+\nu_\ell\text{anything})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_{18}/Γ_4

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
0.58 ±0.05 OUR AVERAGE			
0.594±0.021±0.056	ALBRECHT 94C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.54 ±0.07 ±0.06	[30] ALAM 87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[30] ALAM 87B measurement relies on lepton-kaon correlations.

$\Gamma(K^-\ell^+\nu_\ell\text{anything})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_{19}/Γ_4

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
0.092±0.035 OUR AVERAGE			
0.086±0.011±0.044	ALBRECHT 94C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.10 ±0.05 ±0.02	[31] ALAM 87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[31] ALAM 87B measurement relies on lepton-kaon correlations.

$\Gamma(K^0/\overline{K}^0\ell^+\nu_\ell\text{anything})/\Gamma(\ell^+\nu_\ell\text{anything})$ Γ_{20}/Γ_4

ℓ denotes e or μ, not the sum. Sum over K^0 and $\overline{K}^0$ states.

VALUE	DOCUMENT ID	TECN	COMMENT
0.42 ±0.05 OUR AVERAGE			
0.452±0.038±0.056	[32] ALBRECHT 94C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.39 ±0.06 ±0.04	[33] ALAM 87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[32] ALBRECHT 94C assume a $K^0/\overline{K}^0$ multiplicity twice that of K^0_S.

[33] ALAM 87B measurement relies on lepton-kaon correlations.

$\langle n_c \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
1.10±0.05	[34] GIBBONS 97B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.98±0.16±0.12	[35] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[34] GIBBONS 97B from charm counting using $B(D_s^+ \to \phi\pi) = 0.036 \pm 0.009$ and $B(\Lambda_c^+ \to pK^-\pi^+) = 0.044 \pm 0.006$.

[35] From the difference between K^- and K^+ widths. ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(D^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.241±0.019 OUR AVERAGE				
$0.240 \pm 0.013^{+0.015}_{-0.016}$		[36] GIBBONS 97B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.25 ±0.04 ±0.02		[37] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.23 \pm 0.05^{+0.01}_{-0.02}$		[38] ALBRECHT 91H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.21 ±0.05 ±0.01	20k	[39] BORTOLETTO87	CLEO	Sup. by BORTOLETTO 92

[36] GIBBONS 97B reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.0216 \pm 0.0008 \pm 0.00082$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[37] BORTOLETTO 92 reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.0226 \pm 0.0030 \pm 0.0018$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[38] ALBRECHT 91H reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.0209 \pm 0.0027 \pm 0.0040$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[39] BORTOLETTO 87 reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.019 \pm 0.004 \pm 0.002$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^0/\overline{D}^0\text{anything})/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.631±0.029 OUR AVERAGE		Error includes scale factor of 1.1.		
0.651±0.025±0.015		[40] GIBBONS 97B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.60 ±0.05 ±0.01		[41] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.50 ±0.08 ±0.01		[42] ALBRECHT 91H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.55 ±0.07 ±0.01	21k	[43] BORTOLETTO87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.62 ±0.19 ±0.01		[44] GREEN 83	CLEO	Repl. by BORTOLETTO 87

[40] GIBBONS 97B reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0251 \pm 0.0006 \pm 0.00075$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[41] BORTOLETTO 92 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0233 \pm 0.0012 \pm 0.0014$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[42] ALBRECHT 91H reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0194 \pm 0.0015 \pm 0.0025$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[43] BORTOLETTO 87 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0210 \pm 0.0015 \pm 0.0021$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[44] GREEN 83 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.024 \pm 0.006 \pm 0.004$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^*(2010)^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.227±0.016 OUR AVERAGE				
0.247±0.019±0.01		[45] GIBBONS 97B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.205±0.019±0.007		[46] ALBRECHT 96D	ARG	$e^+e^- \to \Upsilon(4S)$
0.230±0.028±0.009		[47] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28 ±0.05 ±0.01		[48] ALBRECHT 91H	ARG	Sup. by ALBRECHT 96D
$0.22 \pm 0.04^{+0.07}_{-0.04}$	5200	[49] BORTOLETTO87	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.27 \pm 0.06^{+0.08}_{-0.06}$	510	[50] CSORNA 85	CLEO	Repl. by BORTOLETTO 87

[45] GIBBONS 97B reports $B(B \to D^*(2010)^+\text{anything}) = 0.239 \pm 0.015 \pm 0.014 \pm 0.009$ using CLEO measured D and D^* branching fractions. We rescale to our PDG 96 values of D and D^* branching ratios. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[46] ALBRECHT 96D reports $B(B \to D^*(2010)^+\text{anything})$ 0.196 ± 0.019 using CLEO measured $B(D^*(2010)^+ \to D^0\pi^+) = 0.681 \pm 0.01 \pm 0.013$, $B(D^0 \to K^-\pi^+) = 0.0401 \pm 0.0014$, $B(D^0 \to K^-\pi^+\pi^+\pi^-) = 0.081 \pm 0.005$., We rescale to our PDG 96 values of D and D^* branching ratios. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[47] BORTOLETTO 92 reports $B(B \to D^*(2010)^+\text{anything}) = 0.25 \pm 0.03 \pm 0.04$ using MARK II $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$ and $B(D^0 \to K^-\pi^+) = 0.042 \pm 0.008$. We rescale to our PDG 96 values of D and D^* branching ratios. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[48] ALBRECHT 91H reports $0.348 \pm 0.060 \pm 0.035$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.55 \pm 0.04$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Uses the PDG 90 $B(D^0 \to K^-\pi^+) = 0.0371 \pm 0.0025$.

[49] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratios $B(D^0 \to K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$ and also assumes $B(D^*(2010)^+ \to D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. The product branching ratio for $B(B \to D^*(2010)^+)\, B(D^*(2010)^+ \to D^0\pi^+)$ is $0.13 \pm 0.02 \pm 0.012$. Superseded by BORTOLETTO 92.

[50] $V-A$ momentum spectrum used to extrapolate below $p = 1$ GeV. We correct the value assuming $B(D^0 \to K^-\pi^+) = 0.042 \pm 0.006$ and $B(D^{*+} \to D^0\pi^+) = 0.6^{+0.08}_{-0.15}$. The product branching fraction is $B(B \to D^{*+}X) \cdot B(D^{*+} \to \pi^+D^0) \cdot B(D^0 \to K^-\pi^+) = (68 \pm 15 \pm 9) \times 10^{-4}$.

$\Gamma(D^*(2007)^0\text{anything})/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.260±0.023±0.015	[51] GIBBONS 97B	CLE2	$e^+e^- \to \Upsilon(4S)$

[51] GIBBONS 97B reports $B(B \to D^*(2007)^0\text{anything})$ 0.247 ± 0.012 ± 0.018 ± 0.018 using CLEO measured D and D^* branching fractions. We rescale to our PDG 96 values of D and D^* branching ratios. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D_s^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.100±0.025 OUR AVERAGE				
$0.117 \pm 0.009^{+0.028}_{-0.029}$		[52] GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.081 \pm 0.014^{+0.019}_{-0.020}$		[53] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$
$0.085 \pm 0.013^{+0.020}_{-0.021}$	257	[54] BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.105 \pm 0.028^{+0.025}_{-0.026}$		[55] HAAS 86	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.116±0.030±0.028		[56] ALBRECHT 87H	ARG	$e^+e^- \to \Upsilon(4S)$

[52] GIBAUT 96 reports $0.1211 \pm 0.0039 \pm 0.0088$ for $B(D_s^+ \to \phi\pi^+) = 0.035$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[53] ALBRECHT 92G reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.00292 \pm 0.00039 \pm 0.00031$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[54] BORTOLETTO 90 reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.00306 \pm 0.00047$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[55] HAAS 86 reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.0038 \pm 0.0010$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. 64 ± 22% decays are 2-body.

[56] ALBRECHT 87H reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.0042 \pm 0.0009 \pm 0.0006$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. 46 ± 16% of $B \to D_s X$ decays are 2-body. Superseded by ALBRECHT 92G.

$\Gamma(c\overline{c}s)/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.219±0.037	[57] COAN 98	CLE2	$e^+e^- \to \Upsilon(4S)$

[57] COAN 98 uses D-ℓ correlation.

$\Gamma(D_s D,\ D_s^* D,\ D_s D^*,\ \text{or}\ D_s^* D^*)/\Gamma(D_s^{\pm}\text{anything})$ Γ_{27}/Γ_{25}

Sum over modes.

VALUE	DOCUMENT ID	TECN	COMMENT
0.48 ±0.04 OUR AVERAGE			
0.457±0.019±0.037	GIBAUT 96	CLE2	$e^+e^- \to \Upsilon(4S)$
0.58 ±0.07 ±0.09	ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.56 ±0.10	BORTOLETTO90	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(D^*(2010)\gamma)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-3}$	90	[58] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[58] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(D_{s1}(2536)^+ \text{anything})/\Gamma_{\text{total}}$ Γ_{30}/Γ

$D_{s1}(2536)^+$ is the narrow P-wave D_s^+ meson with $J^P = 1^+$.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0095	90	[59] BISHAI	98	CLE2	$e^+e^- \to \Upsilon(4S)$

[59] Assuming factorization, the decay constant $f_{D_{s1}^+}$ is at least a factor of 2.5 times smaller than $f_{D_s^+}$.

$\Gamma(D_s^+\pi^-, D_s^{*+}\pi^-, D_s^+\rho^-, D_s^{*+}\rho^-, D_s^+\pi^0, D_s^{*+}\pi^0, D_s^+\eta, D_s^{*+}\eta, D_s^+\rho^0, D_s^{*+}\rho^0, D_s^+\omega, D_s^{*+}\omega)/\Gamma_{\text{total}}$ Γ_{29}/Γ

Sum over modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[60] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[60] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$. This branching ratio limit provides a model-dependent upper limit $|V_{ub}|/|V_{cb}| < 0.16$ at CL=90%.

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{\text{total}}$ Γ_{31}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
1.13±0.06 OUR AVERAGE					
$1.11\pm0.05\pm0.04$	1489	[61] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
$1.28\pm0.44\pm0.04$	27	[62] MASCHMANN	90	CBAL	$e^+e^- \to \Upsilon(4S)$
$1.23\pm0.27\pm0.04$	120	[63] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
$1.34\pm0.24\pm0.04$	52	[64] ALAM	86	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.4\ ^{+0.6}_{-0.5}$	7	[65] ALBRECHT	85H	ARG	$e^+e^- \to \Upsilon(4S)$
$1.1\ \pm0.21\pm0.23$	46	[66] HAAS	85	CLEO	Repl. by ALAM 86

[61] BALEST 95B reports $1.12 \pm 0.04 \pm 0.06$ for $B(J/\psi(1S) \to e^+e^-) = 0.0599 \pm 0.0025$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.. They measure $J/\psi(1S) \to e^+e^-$ and $\mu^+\mu^-$ and use PDG 1994 values for the branching fractions. The rescaling is the same for either mode so we use e^+e^-.

[62] MASCHMANN 90 reports $1.12\pm0.33\pm0.25$ for $B(J/\psi(1S) \to e^+e^-) = 0.069\pm0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[63] ALBRECHT 87D reports $1.07 \pm 0.16 \pm 0.22$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. ALBRECHT 87D find the branching ratio for J/ψ not from $\psi(2S)$ to be 0.0081 ± 0.0023.

[64] ALAM 86 reports $1.09 \pm 0.16 \pm 0.21$ for $B(J/\psi(1S) \to \mu^+\mu^-) = 0.074 \pm 0.012$. We rescale to our best value $B(J/\psi(1S) \to \mu^+\mu^-) = (6.01 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[65] Statistical and systematic errors were added in quadrature. ALBRECHT 85H also report a CL = 90% limit of 0.007 for $B \to J/\psi(1S) + X$ where m_X <1 GeV.

[66] Dimuon and dielectron events used.

$\Gamma(J/\psi(1S)(\text{direct})\,\text{anything})/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0080±0.0008	[67] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[67] BALEST 95B assume PDG 1994 values for sub mode branching ratios. $J/\psi(1S)$ mesons are reconstructed in $J/\psi(1S) \to e^+e^-$ and $J/\psi(1S) \to \mu^+\mu^-$. The $B \to J/\psi(1S)X$ branching ratio contains $J/\psi(1S)$ mesons directly from B decays and also from feeddown through $\psi(2S) \to J/\psi(1S)$, $\chi_{c1}(1P) \to J/\psi(1S)$, or $\chi_{c2}(1P) \to J/\psi(1S)$. Using the measured inclusive rates, BALEST 95B corrects for the feeddown and finds the $B \to J/\psi(1S)(\text{direct})\,X$ branching ratio.

$\Gamma(\psi(2S)\text{anything})/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0035±0.0005 OUR AVERAGE					
$0.0034\pm0.0004\pm0.0003$	240	[68] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.0046\pm0.0017\pm0.0011$	8	ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[68] BALEST 95B assume PDG 1994 values for sub mode branching ratios. They find $B(B \to \psi(2S)X,\ \psi(2S) \to \ell^+\ell^-) = 0.30 \pm 0.05 \pm 0.04$ and $B(B \to \psi(2S)X,\ \psi(2S) \to J/\psi(1S)\pi^+\pi^-) = 0.37\pm0.05\pm0.05$. Weighted average is quoted for $B(B \to \psi(2S)X)$.

$\Gamma(\chi_{c1}(1P)\text{anything})/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0042±0.0007 OUR AVERAGE					
$0.0040\pm0.0006\pm0.0004$	112	[69] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
$0.0105\pm0.0035\pm0.0025$		[70] ALBRECHT	92E	ARG	$e^+e^- \to \Upsilon(4S)$

[69] BALEST 95B assume $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma) = (27.3 \pm 1.6) \times 10^{-2}$, the PDG 1994 value. Fit to ψ-photon invariant mass distribution allows for a $\chi_{c1}(1P)$ and a $\chi_{c2}(1P)$ component.

[70] ALBRECHT 92E assumes no $\chi_{c2}(1P)$ production.

$\Gamma(\chi_{c1}(1P)(\text{direct})\,\text{anything})/\Gamma_{\text{total}}$ Γ_{35}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037±0.0007	[71] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[71] BALEST 95B assume PDG 1994 values. $J/\psi(1S)$ mesons are reconstructed in the e^+e^- and $\mu^+\mu^-$ modes. The $B \to \chi_{c1}(1P)X$ branching ratio contains $\chi_{c1}(1P)$ mesons directly from B decays and also from feeddown through $\psi(2S) \to \chi_{c1}(1P)\gamma$. Using the measured inclusive rates, BALEST 95B corrects for the feeddown and finds the $B \to \chi_{c1}(1P)(\text{direct})\,X$ branching ratio.

$\Gamma(\chi_{c2}(1P)\text{anything})/\Gamma_{\text{total}}$ Γ_{36}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0038	90	35	[72] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[72] BALEST 95B assume $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma) = (13.5 \pm 1.1) \times 10^{-2}$, the PDG 1994 value. $J/\psi(1S)$ mesons are reconstructed in the e^+e^- and $\mu^+\mu^-$ modes, and PDG 1994 branching fractions are used. If interpreted as signal, the 35 ± 13 events correspond to $B(B \to \chi_{c2}(1P)X) = (0.25 \pm 0.10 \pm 0.03) \times 10^{-2}$.

$\Gamma(\eta_c(1S)\text{anything})/\Gamma_{\text{total}}$ Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	[73] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[73] BALEST 95B assume PDG 1994 values for sub mode branching ratios. $J/\psi(1S)$ mesons are reconstructed in $J/\psi(1S) \to e^+e^-$ and $J/\psi(1S) \to \mu^+\mu^-$. Search region $2960 < m_{\eta_c(1S)} < 3010$ MeV/c^2.

$\Gamma(K^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_{38}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.789±0.025 OUR AVERAGE				
$0.82\ \pm0.01\ \pm0.05$	ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.775\pm0.015\pm0.025$	[74] ALBRECHT	93I	ARG	$e^+e^- \to \Upsilon(4S)$
$0.85\ \pm0.07\ \pm0.09$	ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	[75] BRODY	82	CLEO	$e^+e^- \to \Upsilon(4S)$
seen	[76] GIANNINI	82	CUSB	$e^+e^- \to \Upsilon(4S)$

[74] ALBRECHT 93I value is not independent of the sum of $B \to K^+$ anything and $B \to K^-$ anything ALBRECHT 94C values.

[75] Assuming $\Upsilon(4S) \to B\overline{B}$, a total of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay is found (the second error is systematic). In the context of the standard B-decay model, this leads to a value for (b-quark → c-quark)/(b-quark → all) of $1.09 \pm 0.33 \pm 0.13$.

[76] GIANNINI 82 at CESR-CUSB observed 1.58 ± 0.35 K^0 per hadronic event much higher than 0.82 ± 0.10 below threshold. Consistent with predominant $b \to cX$ decay.

$\Gamma(K^+\text{anything})/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.66 ±0.05	[77] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.620\pm0.013\pm0.038$	[78] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.66\ \pm0.05\ \pm0.07$	[78] ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[77] Measurement relies on lepton-kaon correlations. It is for the weak decay vertex and does not include mixing of the neutral B meson. Mixing effects were corrected for by assuming a mixing parameter r of (18.1 ± 4.3)%.

[78] Measurement relies on lepton-kaon correlations. It includes production through mixing of the neutral B meson.

$\Gamma(K^-\text{anything})/\Gamma_{\text{total}}$ Γ_{40}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.13 ±0.04	[79] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.165\pm0.011\pm0.036$	[80] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.19\ \pm0.05\ \pm0.02$	[80] ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[79] Measurement relies on lepton-kaon correlations. It is for the weak decay vertex and does not include mixing of the neutral B meson. Mixing effects were corrected for by assuming a mixing parameter r of (18.1 ± 4.3)%.

[80] Measurement relies on lepton-kaon correlations. It includes production through mixing of the neutral B meson.

$\Gamma(K^0/\overline{K}^0\text{anything})/\Gamma_{\text{total}}$ Γ_{41}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.64 ±0.04 OUR AVERAGE				
$0.642\pm0.010\pm0.042$	[81] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.63\ \pm0.06\ \pm0.06$	ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[81] ALBRECHT 94C assume a $K^0/\overline{K}^0$ multiplicity twice that of K_S^0.

$\Gamma(K^*(892)^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_{42}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.182±0.054±0.024	ALBRECHT	94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0/\overline{K}^*(892)^0\text{anything})/\Gamma_{\text{total}}$ Γ_{43}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.146±0.016±0.020	ALBRECHT	94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)\gamma)/\Gamma_{\text{total}}$ Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-3}$	90	[82] LESIAK	92	CBAL	$e^+e^- \to \Upsilon(4S)$
$<2.4 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \to \Upsilon(4S)$

[82] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(K_1(1400)\gamma)/\Gamma_{\rm total}$ Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.1 \times 10^{-4}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-3}$	90	[83] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[83] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(K_2^*(1430)\gamma)/\Gamma_{\rm total}$ Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.3 \times 10^{-4}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2(1770)\gamma)/\Gamma_{\rm total}$ Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-3}$	90	[84] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[84] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(K_3^*(1780)\gamma)/\Gamma_{\rm total}$ Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_4^*(2045)\gamma)/\Gamma_{\rm total}$ Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[85] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[85] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(\overline{b} \to \overline{s}\gamma)/\Gamma_{\rm total}$ Γ_{50}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$	ALAM 95	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{b} \to \overline{s}\,\text{gluon})/\Gamma_{\rm total}$ Γ_{51}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.068	90		[86] COAN 98	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.08		2	[87] ALBRECHT 95D	ARG	$e^+e^- \to \Upsilon(4S)$

[86] COAN 98 uses D-ℓ correlation.

[87] ALBRECHT 95D use full reconstruction of one B decay as tag. Two candidate events for charmless B decay can be interpreted as either $b \to s$gluon or $b \to u$ transition. If interpreted as $b \to s$gluon they find a branching ratio of ~ 0.026 or the upper limit quoted above. Result is highly model dependent.

$\Gamma(\pi^{\pm}\text{ anything})/\Gamma_{\rm total}$ Γ_{52}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$3.585 \pm 0.025 \pm 0.070$	[88] ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$

[88] ALBRECHT 93 excludes $\pi^{\pm}$ from K_S^0 and Λ decays. If included, they find $4.105 \pm 0.025 \pm 0.080$.

$\Gamma(\eta\text{ anything})/\Gamma_{\rm total}$ Γ_{53}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.176 \pm 0.011 \pm 0.012$	KUBOTA 96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\rho^0\text{ anything})/\Gamma_{\rm total}$ Γ_{54}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.208 \pm 0.042 \pm 0.032$	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\omega\text{ anything})/\Gamma_{\rm total}$ Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.81	90	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\phi\text{ anything})/\Gamma_{\rm total}$ Γ_{56}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.035 ± 0.007 OUR AVERAGE	Error includes scale factor of 1.8.		
$0.0390 \pm 0.0030 \pm 0.0035$	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.023 \pm 0.006 \pm 0.005$	BORTOLETTO 86	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda_c^{\pm}\text{ anything})/\Gamma_{\rm total}$ Γ_{57}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$0.064 \pm 0.008 \pm 0.008$		[89] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.14 ± 0.09		[90] ALBRECHT 88E	ARG	$e^+e^- \to \Upsilon(4S)$
<0.112	90	[91] ALAM 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[89] CRAWFORD 92 result derived from lepton baryon correlations. Assumes all charmed baryons in B^0 and $B^{\pm}$ decay are Λ_c.

[90] ALBRECHT 88E measured $B(B \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^-\pi^+) = (0.30 \pm 0.12 \pm 0.06)\%$ and used $B(\Lambda_c^+ \to pK^-\pi^+) = (2.2 \pm 1.0)\%$ from ABRAMS 80 to obtain above number.

[91] Assuming all baryons result from charmed baryons, ALAM 86 conclude the branching fraction is $7.4 \pm 2.9\%$. The limit given above is model independent.

$\Gamma(\Lambda_c^+\text{ anything})/\Gamma(\Lambda_c^-\text{ anything})$ Γ_{58}/Γ_{59}

VALUE	DOCUMENT ID	TECN	COMMENT
$0.19 \pm 0.13 \pm 0.04$	[92] AMMAR 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[92] AMMAR 97 uses a high-momentum lepton tag ($P_\ell > 1.4$ GeV/c^2).

$\Gamma(\Lambda_c^- e^+\text{ anything})/\Gamma(\Lambda_c^{\pm}\text{ anything})$ Γ_{60}/Γ_{57}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	[93] BONVICINI 98	CLE2	$e^+e^- \to \Upsilon(4S)$

[93] BONVICINI 98 uses the electron with momentum above 0.6 GeV/c.

$\Gamma(\Lambda_c^- p\,\text{anything})/\Gamma(\Lambda_c^{\pm}\text{ anything})$ Γ_{61}/Γ_{57}

VALUE	DOCUMENT ID	TECN	COMMENT
$0.57 \pm 0.05 \pm 0.05$	BONVICINI 98	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda_c^- p e^+ \nu_e)/\Gamma(\Lambda_c^- p\,\text{anything})$ Γ_{62}/Γ_{61}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.04	90	[94] BONVICINI 98	CLE2	$e^+e^- \to \Upsilon(4S)$

[94] BONVICINI 98 uses the electron with momentum above 0.6 GeV/c.

$\Gamma(\overline{\Sigma}_c^{--}\text{ anything})/\Gamma_{\rm total}$ Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0042 \pm 0.0021 \pm 0.0011$	77	[95] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[95] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{--}\text{ anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = 0.00021 \pm 0.00008 \pm 0.00007$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{\Sigma}_c^{-}\text{ anything})/\Gamma_{\rm total}$ Γ_{64}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.010	90	[96] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[96] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{-}\text{ anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = < 0.00048$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.050$.

$\Gamma(\overline{\Sigma}_c^{0}\text{ anything})/\Gamma_{\rm total}$ Γ_{65}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0046 \pm 0.0021 \pm 0.0012$	76	[97] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[97] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{0}\text{ anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = 0.00023 \pm 0.00008 \pm 0.00007$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{\Sigma}_c^{0} N (N = p \text{ or } n))/\Gamma_{\rm total}$ Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0015	90	[98] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[98] PROCARIO 94 reports < 0.0017 for $B(\Lambda_c^+ \to pK^-\pi^+) = 0.043$. We rescale to our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.050$.

$\Gamma(\Xi_c^0\text{ anything} \times B(\Xi_c^0 \to \Xi^-\pi^+))/\Gamma_{\rm total}$ Γ_{67}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$0.144 \pm 0.048 \pm 0.021$	[99] BARISH 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[99] BARISH 97 find 79 ± 27 Ξ_c^0 events.

$\Gamma(\Xi_c^+\text{ anything} \times B(\Xi_c^+ \to \Xi^-\pi^+\pi^+))/\Gamma_{\rm total}$ Γ_{68}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$0.453 \pm 0.096^{+0.085}_{-0.065}$	[100] BARISH 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[100] BARISH 97 find 125 ± 28 Ξ_c^+ events.

$\Gamma(p/\overline{p}\,\text{anything})/\Gamma_{\rm total}$ Γ_{69}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.080 ± 0.004 OUR AVERAGE				
$0.080 \pm 0.005 \pm 0.005$		ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$
$0.080 \pm 0.005 \pm 0.003$		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.082 \pm 0.005^{+0.013}_{-0.010}$	2163	[101] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.021		[102] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[101] ALBRECHT 89K include direct and nondirect protons.

[102] ALAM 83B reported their result as $> 0.036 \pm 0.006 \pm 0.009$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to p + X) = 0.03$ not including protons from Λ decays.

$\Gamma(p/\overline{p}(\text{direct})\text{ anything})/\Gamma_{\rm total}$ Γ_{70}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055 ± 0.005 OUR AVERAGE				
$0.055 \pm 0.005 \pm 0.0035$		ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$
$0.056 \pm 0.006 \pm 0.005$		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.055 ± 0.016	1220	[103] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[103] ALBRECHT 89K subtract contribution of Λ decay from the inclusive proton yield.

$\Gamma(\Lambda/\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ Γ_{71}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.040±0.005 OUR AVERAGE				
0.038±0.004±0.006	2998	CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.042±0.005±0.006	943	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022±0.003±0.0022		[104] ACKERSTAFF 97N	OPAL	$e^+e^- \to Z$
>0.011		[105] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[104] ACKERSTAFF 97N assues $B(b \to B) = 0.868 \pm 0.041$, *i.e.*, an admixture of B^0, $B^{\pm}$, and B_s.

[105] ALAM 83B reported their result as $> 0.022 \pm 0.007 \pm 0.004$. Values are for $(B(\Lambda X)+B(\overline{\Lambda}X))/2$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to \Lambda X) = 0.03$.

$\Gamma(\Lambda\text{anything})/\Gamma(\overline{\Lambda}\text{anything})$ Γ_{72}/Γ_{73}

VALUE	DOCUMENT ID	TECN	COMMENT
0.43±0.09±0.07	[106] AMMAR 97	CLE2	$e^+e^- \to \Upsilon(4S)$

[106] AMMAR 97 uses a high-momentum lepton tag ($P_\ell > 1.4$ GeV/c^2).

$\Gamma(\Xi^-/\overline{\Xi}^+\text{anything})/\Gamma_{\text{total}}$ Γ_{74}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0027±0.0006 OUR AVERAGE				
0.0027±0.0005±0.0004	147	CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0028±0.0014	54	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{baryons anything})/\Gamma_{\text{total}}$ Γ_{75}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.068±0.005±0.003	[107] ALBRECHT 92O	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.076±0.014	[108] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[107] ALBRECHT 92O result is from simultaneous analysis of p and Λ yields, $p\overline{p}$ and $\Lambda\overline{p}$ correlations, and various lepton-baryon and lepton-baryon-antibaryon correlations. Supersedes ALBRECHT 89K.

[108] ALBRECHT 89K obtain this result by adding their their measurements (5.5 ± 1.6)% for direct protons and (4.2 ± 0.5 ± 0.6)% for inclusive Λ production. They then assume (5.5 ± 1.6)% for neutron production and add it in also. Since each B decay has two baryons, they divide by 2 to obtain (7.6 ± 1.4)%.

$\Gamma(p\overline{p}\text{anything})/\Gamma_{\text{total}}$ Γ_{76}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0247±0.0023 OUR AVERAGE				
0.024 ±0.001 ±0.004		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.025 ±0.002 ±0.002	918	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p}\text{anything})/\Gamma(p/\overline{p}\text{anything})$ Γ_{76}/Γ_{69}

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.30±0.02±0.05	[109] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[109] CRAWFORD 92 value is not independent of their $\Gamma(p\overline{p}\text{anything})/\Gamma_{\text{total}}$ value.

$\Gamma(\Lambda\overline{p}/\overline{\Lambda}p\text{anything})/\Gamma_{\text{total}}$ Γ_{77}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.025±0.004 OUR AVERAGE				
0.029±0.005±0.005		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.023±0.004±0.003	165	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{p}/\overline{\Lambda}p\text{anything})/\Gamma(\Lambda/\overline{\Lambda}\text{anything})$ Γ_{77}/Γ_{71}

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.76±0.11±0.08	[110] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[110] CRAWFORD 92 value is not independent of their $[\Gamma(\Lambda\overline{p}\text{anything})+\Gamma(\overline{\Lambda}p\text{anything})]/\Gamma_{\text{total}}$ value.

$\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ Γ_{78}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.005	90		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0088	90	12	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma(\Lambda/\overline{\Lambda}\text{anything})$ Γ_{78}/Γ_{71}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.13	90	[111] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[111] CRAWFORD 92 value is not independent of their $\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ value.

$\Gamma(e^+e^-s)/\Gamma_{\text{total}}$ Γ_{79}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.7 × 10^{-5}	90	GLENN 98	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	90	BEBEK 81	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\mu^+\mu^-s)/\Gamma_{\text{total}}$ Γ_{80}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.8 × 10^{-5}	90	GLENN 98	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.017	90	CHADWICK 81	CLEO	$e^+e^- \to \Upsilon(4S)$

$[\Gamma(e^+e^-s)+\Gamma(\mu^+\mu^-s)]/\Gamma_{\text{total}}$ $(\Gamma_{79}+\Gamma_{80})/\Gamma$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.2 × 10^{-5}	90	GLENN 98	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0024	90	[112] BEAN 87	CLEO	Repl. by GLENN 98
<0.0062	90	[113] AVERY 84	CLEO	Repl. by BEAN 87

[112] BEAN 87 reports $[(\mu^+\mu^-)+(e^+e^-)]/2$ and we converted it.

[113] Determine ratio of B^+ to B^0 semileptonic decays to be in the range 0.25–2.9.

$\Gamma(e^{\pm}\mu^{\mp}s)/\Gamma_{\text{total}}$ Γ_{81}/Γ

Test for lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.2 × 10^{-5}	90	GLENN 98	CLEO	$e^+e^- \to \Upsilon(4S)$

$B^{\pm}/B^0$ ADMIXTURE REFERENCES

BISHAI	98	PR D57 3847	M. Bishai+	(CLEO Collab.)
BONVICINI CLNS 97/1519	98	PR D (to be publ.)	G. Bonvicini+	(CLEO Collab.)
COAN	98	PRL 80 1150	T.E. Coan+	(CLEO Collab.)
GLENN	98	PRL 80 2289	S. Glenn+	(CLEO Collab.)
ACKERSTAFF	97N	ZPHY C74 423	K. Ackerstaff+	(OPAL Collab.)
AMMAR	97	PR D55 13	R. Ammar+	(CLEO Collab.)
BARISH	97	PRL 79 3599	B. Barish+	(CLEO Collab.)
BUSKULIC	97B	ZPHY C73 601	D. Buskulic+	(ALEPH Collab.)
GIBBONS	97B	PR D56 3783	L. Gibbons+	(CLEO Collab.)
ALBRECHT	96D	PL B374 256	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
BARISH	96B	PRL 76 1570	+Chadha, Chan, Eigen+	(CLEO Collab.)
GIBAUT	96	PR D53 4734	+Kinoshita, Pomianowski, Barish+	(CLEO Collab.)
KUBOTA	96	PR D53 6033	+Lattery, Momayezi, Nelson+	(CLEO Collab.)
PDG	96	PR D54 1		
ALAM	95	PRL 74 2885	+Kim, Ling, Mahmood+	(CLEO Collab.)
ALBRECHT	95D	PL B353 554	+Hamacher, Hofmann, Kirchoff+	(ARGUS Collab.)
BALEST	95B	PR D52 2661	+Cho, Ford, Johnson+	(CLEO Collab.)
BARISH	95	PR D51 1014	+Chadha, Chan, Cowen+	(CLEO Collab.)
BUSKULIC	95B	PL B345 103	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ALBRECHT	94C	ZPHY C62 371	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	94J	ZPHY C61 1	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
PROCARIO	94	PRL 73 1306	+Balest, Cho, Daoudi, Ford+	(CLEO Collab.)
ALBRECHT	93	ZPHY C57 533	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93E	ZPHY C60 11	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93H	PL B318 397	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93I	ZPHY C58 191	+Cronstroem, Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALEXANDER	93B	PL B319 365	+Bebek, Berkelman, Bloom, Browder+	(CLEO Collab.)
ARTUSO	93	PL B311 307		(SYRA)
BARTELT	93B	PRL 71 4111	+Csorna, Egyed, Jain, Akerib+	(CLEO Collab.)
ALBRECHT	92E	PL B277 209	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92G	ZPHY C54 1	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92O	ZPHY C56 1	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
BORTOLETTO	92	PR D45 21	+Brown, Dominick, Mcllwain+	(CLEO Collab.)
CRAWFORD	92	PR D45 752	+Fulton, Jensen, Johnson+	(CLEO Collab.)
HENDERSON	92	PR D45 2212	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
LESIAK	92	ZPHY C55 33	+Antreasyan, Bartels, Besset, Bieler+	(Crystal Ball Collab.)
ALBRECHT	91C	PL B255 297	+Ehrlichmann, Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	91H	ZPHY C52 353	+Ehrlichmann, Hamacher, Harder+	(ARGUS Collab.)
FULTON	91	PR D43 651	+Jensen, Johnson, Kagan, Kass+	(CLEO Collab.)
YANAGISAWA	91	PRL 66 2436	+Heintz, Lee-Franzini, Lovelock, Narain+	(CUSB II Collab.)
ALBRECHT	90	PL B234 409	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	90H	PL B249 359	+Ehrlichmann, Glaeser, Harder, Krueger+	(Argus Collab.)
BORTOLETTO	90	PRL 64 2117	+Goldberg, Horwitz, Jain, Mestayer+	(CLEO Collab.)
Also	92	PR D45 21	Bortoletto, Brown, Dominick, Mcllwain+	(CLEO Collab.)
FULTON	90	PRL 64 16	+Hempstead, Jensen, Johnson+	(CLEO Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
PDG	90	PL B239	Hernandez, Stone, Porter+	(IFIC, BOST, CIT+)
ALBRECHT	89K	ZPHY C42 519	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ISGUR	89B	PR D39 799	+Scora, Grinstein, Wise	(TNTO, CIT)
WACHS	89	ZPHY C42 33	+Antreasyan, Bartels, Bieler+	(Crystal Ball Collab.)
ALBRECHT	88E	PL B210 263	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88H	PL B210 258	+Boeckmann, Glaeser+	(ARGUS Collab.)
KOERNER	88	ZPHY C38 511	+Schuler	(MANZ, DESY)
ALAM	87	PRL 59 22	+Kitukama, Kim, Li+	(CLEO Collab.)
ALAM	87B	PRL 58 1814	+Katayama, Kim, Sun+	(CLEO Collab.)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	87H	PL B187 425	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
BEAN	87	PR D35 3533	+Bobbink, Brock, Engler+	(CLEO Collab.)
BEHRENDS	87	PRL 59 407	+Morrow, Guida, Guida+	(CLEO Collab.)
BORTOLETTO	87	PR D35 19	+Chen, Garren, Goldberg+	(CLEO Collab.)
ALAM	86	PR D34 3279	+Katayama, Kim, Sun+	(CLEO Collab.)
BALTRUSAIT...	86E	PRL 56 2140	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BORTOLETTO	86	PRL 56 800	+Chen, Garren, Goldberg+	(CLEO Collab.)
HAAS	86	PRL 56 2781	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
ALBRECHT	85H	PL 162B 395	+Binder, Harder+	(ARGUS Collab.)
CSORNA	85	PRL 54 1894	+Garren, Mestayer, Panvini+	(CLEO Collab.)
HAAS	85	PRL 55 1248	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
AVERY	84	PRL 53 1309	+Bebek, Berkelman, Cassel+	(CLEO Collab.)
CHEN	84	PRL 52 1084	+Goldberg, Horwitz, Jawahery+	(CLEO Collab.)
LEVMAN	84	PL 141B 271	+Sreedhar, Han, Imlay+	(CUSB Collab.)
ALAM	83B	PRL 51 1143	+Csorna, Garren, Mestayer+	(CLEO Collab.)
GREEN	83	PRL 51 347	+Hicks, Sannes, Skubic+	(CLEO Collab.)
KLOPFEN...	83B	PL 130B 444	Klopfenstein, Horstkotte+	(CUSB Collab.)
ALTARELLI	82	NP B208 365	+Cabibbo, Corbo, Maini, Martinelli	(ROMA, INFN, FRAS)
BRODY	82	PRL 48 1070	+Chen, Goldberg, Horwitz+	(CLEO Collab.)
GIANNINI	82	NP B206 1	+Finocchiaro, Franzini+	(CUSB Collab.)
BEBEK	81	PRL 46 84	+Haggerty, izen, Longuemare+	(CLEO Collab.)
CHADWICK	81	PRL 46 88	+Ganci, Kagar, Kass+	(CLEO Collab.)
ABRAMS	80	PRL 44 10	+Alam, Blocker, Boyarski+	(SLAC, LBL)

$B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE

$B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE MEAN LIFE

Each measurement of the B mean life is an average over an admixture of various bottom mesons and baryons which decay weakly. Different techniques emphasize different admixtures of produced particles, which could result in a different B mean life.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetime Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of these Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors, but ignores the small differences due to different techniques.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.564±0.014 OUR EVALUATION					
$1.533\pm0.015^{+0.035}_{-0.031}$		[1] ABE	98B	CDF	$p\overline{p}$ at 1.8 TeV
$1.549\pm0.009\pm0.015$		[2] ACCIARRI	98	L3	$e^+e^- \rightarrow Z$
$1.611\pm0.010\pm0.027$		[3] ACKERSTAFF	97F	OPAL	$e^+e^- \rightarrow Z$
$1.582\pm0.011\pm0.027$		[3] ABREU	96E	DLPH	$e^+e^- \rightarrow Z$
$1.533\pm0.013\pm0.022$	19.8k	[4] BUSKULIC	96F	ALEP	$e^+e^- \rightarrow Z$
$1.564\pm0.030\pm0.036$		[5] ABE,K	95B	SLD	$e^+e^- \rightarrow Z$
$1.542\pm0.021\pm0.045$		[6] ABREU	94L	DLPH	$e^+e^- \rightarrow Z$
$1.523\pm0.034\pm0.038$	5372	[7] ACTON	93L	OPAL	$e^+e^- \rightarrow Z$
$1.535\pm0.035\pm0.028$	7357	[7] ADRIANI	93K	L3	$e^+e^- \rightarrow Z$
$1.511\pm0.022\pm0.078$		[8] BUSKULIC	93O	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.575\pm0.010\pm0.026$		[9] ABREU	96E	DLPH	$e^+e^- \rightarrow Z$
$1.50\ ^{+0.24}_{-0.21}\ \pm0.03$		[10] ABREU	94P	DLPH	$e^+e^- \rightarrow Z$
$1.46\ \pm0.06\ \pm0.06$	5344	[11] ABE	93J	CDF	Repl. by ABE 98B
$1.23\ ^{+0.14}_{-0.13}\ \pm0.15$	188	[12] ABREU	93D	DLPH	Sup. by ABREU 94L
$1.49\ \pm0.11\ \pm0.12$	253	[13] ABREU	93G	DLPH	Sup. by ABREU 94L
$1.51\ ^{+0.16}_{-0.14}\ \pm0.11$	130	[14] ACTON	93C	OPAL	$e^+e^- \rightarrow Z$
$1.28\ \pm0.10$		[15] ABREU	92	DLPH	Sup. by ABREU 94L
$1.37\ \pm0.07\ \pm0.06$	1354	[16] ACTON	92	OPAL	Sup. by ACTON 93L
$1.49\ \pm0.03\ \pm0.06$		[17] BUSKULIC	92F	ALEP	Sup. by BUSKULIC 96F
$1.35\ ^{+0.19}_{-0.17}\ \pm0.05$		[18] BUSKULIC	92G	ALEP	$e^+e^- \rightarrow Z$
$1.32\ \pm0.08\ \pm0.09$	1386	[19] ADEVA	91H	L3	Sup. by ADRIANI 93K
$1.32\ ^{+0.31}_{-0.25}\ \pm0.15$	37	[20] ALEXANDER	91G	OPAL	$e^+e^- \rightarrow Z$
$1.29\ \pm0.06\ \pm0.10$	2973	[21] DECAMP	91C	ALEP	Sup. by BUSKULIC 92F
$1.36\ ^{+0.25}_{-0.23}$		[22] HAGEMANN	90	JADE	E^{ee}_{cm}= 35 GeV
$1.13\ \pm0.15$		[23] LYONS	90	RVUE	
$1.35\ \pm0.10\ \pm0.24$		BRAUNSCH...	89B	TASS	E^{ee}_{cm}= 35 GeV
$0.98\ \pm0.12\ \pm0.13$		ONG	89	MRK2	E^{ee}_{cm}= 29 GeV
$1.17\ ^{+0.27}_{-0.22}\ ^{+0.17}_{-0.16}$		KLEM	88	DLCO	E^{ee}_{cm}= 29 GeV
$1.29\ \pm0.20\ \pm0.21$		[24] ASH	87	MAC	E^{ee}_{cm}= 29 GeV
$1.02\ ^{+0.42}_{-0.39}$	301	[25] BROM	87	HRS	E^{ee}_{cm}= 29 GeV

[1] Measured using inclusive $J/\psi(1S) \rightarrow \mu^+\mu^-$ vertex.

[2] ACCIARRI 98 uses inclusively reconstructed secondary vertex and lepton impact parameter.

[3] ACKERSTAFF 97F uses inclusively reconstructed secondary vertices.

[4] BUSKULIC 96F analyzed using 3D impact parameter.

[5] ABE,K 95B uses an inclusive topological technique.

[6] ABREU 94L uses charged particle impact parameters. Their result from inclusively reconstructed secondary vertices is superseded by ABREU 96E.

[7] ACTON 93L and ADRIANI 93K analyzed using lepton (e and μ) impact parameter at Z.

[8] BUSKULIC 93O analyzed using dipole method.

[9] Combines ABREU 96E secondary vertex result with ABREU 94L impact parameter result.

[10] From proper time distribution of $b \rightarrow J/\psi(1S)$anything.

[11] ABE 93J analyzed using $J/\psi(1S) \rightarrow \mu\mu$ vertices.

[12] ABREU 93D data analyzed using $D/D^*\ell$anything event vertices.

[13] ABREU 93G data analyzed using charged and neutral vertices.

[14] ACTON 93C analysed using $D/D^*\ell$anything event vertices.

[15] ABREU 92 is combined result of muon and hadron impact parameter analyses. Hadron tracks gave $(12.7 \pm 0.4 \pm 1.2) \times 10^{-13}$ s for an admixture of B species weighted by production fraction and mean charge multiplicity, while muon tracks gave $(13.0\pm1.0\pm0.8)\times 10^{-13}$ s for an admixture weighted by production fraction and semileptonic branching fraction.

[16] ACTON 92 is combined result of muon and electron impact parameter analyses.

[17] BUSKULIC 92F uses the lepton impact parameter distribution for data from the 1991 run.

[18] BUSKULIC 92G use $J/\psi(1S)$ tags to measure the average b lifetime. This is comparable to other methods only if the $J/\psi(1S)$ branching fractions of the different b-flavored hadrons are in the same ratio.

[19] Using $Z \rightarrow e^+ X$ or $\mu^+ X$, ADEVA 91H determined the average lifetime for an admixture of B hadrons from the impact parameter distribution of the lepton.

[20] Using $Z \rightarrow J/\psi(1S)X$, $J/\psi(1S) \rightarrow \ell^+\ell^-$, ALEXANDER 91G determined the average lifetime for an admixture of B hadrons from the decay point of the $J/\psi(1S)$.

[21] Using $Z \rightarrow eX$ or μX, DECAMP 91C determines the average lifetime for an admixture of B hadrons from the signed impact parameter distribution of the lepton.

[22] HAGEMANN 90 uses electrons and muons in an impact parameter analysis.

[23] LYONS 90 combine the results of the B lifetime measuresments of ONG 89, BRAUNSCHWEIG 89B, KLEM 88, and ASH 87, and JADE data by private communication. They use statistical techniques which include variation of the error with the mean life, and possible correlations between the systematic errors. This result is not independent of the measured results used in our average.

[24] We have combined an overall scale error of 15% in quadrature with the systematic error of ±0.7 to obtain ±2.1 systematic error.

[25] Statistical and systematic errors were combined by BROM 87.

CHARGED b-HADRON ADMIXTURE MEAN LIFE

VALUE (10^{-12} s)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.72±0.08±0.06	[26] ADAM	95	DLPH	$e^+e^- \rightarrow Z$

[26] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

NEUTRAL b-HADRON ADMIXTURE MEAN LIFE

VALUE (10^{-12} s)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.58±0.11±0.09	[27] ADAM	95	DLPH	$e^+e^- \rightarrow Z$

[27] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

MEAN LIFE RATIO $\tau_{\text{charged } b-\text{hadron}}/\tau_{\text{neutral } b-\text{hadron}}$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{1.09^{+0.11}_{-0.10}\pm0.08}$	[28] ADAM	95	DLPH	$e^+e^- \rightarrow Z$

[28] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

$\overline{b}$ PRODUCTION FRACTIONS AND DECAY MODES

The branching fraction measurements are for an admixture of B mesons and baryons at energies above the $\Upsilon(4S)$. Only the highest energy results (LEP, Tevatron, $Sp\overline{p}S$) are used in the branching fraction averages. The production fractions give our best current estimate of the admixture at LEP.

For inclusive branching fractions, *e.g.*, $B \rightarrow D^\pm$anything, the treatment of multiple D's in the final state must be defined. One possiblity would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

The modes below are listed for a $\overline{b}$ initial state. b modes are their charge conjugates. Reactions indicate the weak decay vertex and do not include mixing.

	Mode	Fraction (Γ_i/Γ)	Confidence level

PRODUCTION FRACTIONS

The production fractions for weakly decaying b-hadrons at the Z have been calculated from the best values of mean lives, mixing parameters, and branching fractions in this edition by the LEP B Oscillation Working Group as described in the note "Production and Decay of b-Flavored Hadrons" in the $B^\pm$ Particle Listings. Values assume

$$\mathrm{B}(\overline{b} \rightarrow B^+) = \mathrm{B}(\overline{b} \rightarrow B^0)$$
$$\mathrm{B}(\overline{b} \rightarrow B^+) + \mathrm{B}(\overline{b} \rightarrow B^0) + \mathrm{B}(\overline{b} \rightarrow B^0_s) + \mathrm{B}(b \rightarrow \Lambda_b) = 100\ \%.$$

The notation for production fractions varies in the literature (f_{B^0}, $f(b \rightarrow \overline{B}^0)$, $\mathrm{Br}(b \rightarrow \overline{B}^0)$). We use our own branching fraction notation here, $\mathrm{B}(\overline{b} \rightarrow B^0)$.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	B^+	$(39.7\ ^{+1.8}_{-2.2})$ %	
Γ_2	B^0	$(39.7\ ^{+1.8}_{-2.2})$ %	
Γ_3	B^0_s	$(10.5\ ^{+1.8}_{-1.7})$ %	
Γ_4	Λ_b	$(10.1\ ^{+3.9}_{-3.1})$ %	
Γ_5	B_c		

DECAY MODES

Semileptonic and leptonic modes

Γ_6	ν anything		(23.1 ± 1.5) %	
Γ_7	$\ell^+ \nu_\ell$ anything	[a,b]	(10.99 ± 0.23) %	
Γ_8	$e^+ \nu_e$ anything	[a]	(10.9 ± 0.5) %	
Γ_9	$\mu^+ \nu_\mu$ anything	[a]	(10.8 ± 0.5) %	
Γ_{10}	$D^- \ell^+ \nu_\ell$ anything	[b]	(2.02 ± 0.29) %	
Γ_{11}	$\overline{D}^0 \ell^+ \nu_\ell$ anything	[b]	(6.5 ± 0.6) %	
Γ_{12}	$D^{*-} \ell^+ \nu_\ell$ anything	[b]	(2.76 ± 0.29) %	
Γ_{13}	$\overline{D}^0_J \ell^+ \nu_\ell$ anything	[b,c]	seen	
Γ_{14}	$D^-_J \ell^+ \nu_\ell$ anything	[b,c]	seen	
Γ_{15}	$\overline{D}^*_2(2460)^0 \ell^+ \nu_\ell$ anything		seen	
Γ_{16}	$D^*_2(2460)^- \ell^+ \nu_\ell$ anything		seen	
Γ_{17}	$\tau^+ \nu_\tau$ anything		(2.6 ± 0.4) %	
Γ_{18}	$\overline{c} \to \ell^- \overline{\nu}_\ell$ anything	[b]	(7.8 ± 0.6) %	

Charmed meson and baryon modes

Γ_{19}	$\overline{D}^0$ anything		(60.1 ± 3.2) %	
Γ_{20}	D^- anything		(23.7 ± 2.3) %	
Γ_{21}	$\overline{D}_s$ anything		(18 ± 5) %	
Γ_{22}	Λ_c anything		(9.7 ± 2.9) %	
Γ_{23}	$\overline{c}/c$ anything	[d]	(117 ± 4) %	

Charmonium modes

Γ_{24}	$J/\psi(1S)$ anything		(1.16 ± 0.10) %	
Γ_{25}	$\psi(2S)$ anything		(4.8 ± 2.4) $\times 10^{-3}$	
Γ_{26}	$\chi_{c1}(1P)$ anything		(1.8 ± 0.5) %	

K or K^* modes

Γ_{27}	$\overline{s}\gamma$		$< 5.4 \times 10^{-4}$	90%
Γ_{28}	$K^{\pm}$ anything		(88 ± 19) %	
Γ_{29}	K^0_S anything		(29.0 ± 2.9) %	

Pion modes

Γ_{30}	π^0 anything	[d]	(278 ± 60) %	

Baryon modes

Γ_{31}	$p/\overline{p}$ anything		(14 ± 6) %	

Other modes

Γ_{32}	charged anything	[d]	(497 ± 7) %	
Γ_{33}	hadron$^+$ hadron$^-$		($1.7^{+1.0}_{-0.7}$) $\times 10^{-5}$	
Γ_{34}	charmless		(7 ± 21) $\times 10^{-3}$	

Baryon modes

Γ_{35}	$\Lambda/\overline{\Lambda}$ anything		(5.9 ± 0.6) %	

$\Delta B = 1$ weak neutral current ($B1$) modes

Γ_{36}	$e^+ e^-$ anything			
Γ_{37}	$\mu^+ \mu^-$ anything	$B1$	$< 3.2 \times 10^{-4}$	90%
Γ_{38}	$\nu\overline{\nu}$ anything			

[a] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[b] An ℓ indicates an e or a μ mode, not a sum over these modes.

[c] D_J represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

[d] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE BRANCHING RATIOS

$\Gamma(\nu\text{anything})/\Gamma_{\text{total}}$ $\qquad \Gamma_6/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.2308±0.0077±0.0124	[29,30] ACCIARRI 96C	L3	$e^+e^- \to Z$

[29] ACCIARRI 96C assumes relative b semileptonic decay rates $e{:}\mu{:}\tau$ of 1:1:0.25. Based on missing-energy spectrum.

[30] Assumes Standard Model value for R_B.

$\Gamma(\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}}$ $\qquad \Gamma_7/\Gamma$

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
0.1099±0.0023 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.		
0.1106±0.0039±0.0022	[31] ABREU 95D	DLPH	$e^+e^- \to Z$
0.114 ±0.003 ±0.004	[32] BUSKULIC 94G	ALEP	$e^+e^- \to Z$
0.105 ±0.006 ±0.005	[33] AKERS 93B	OPAL	$e^+e^- \to Z$

[31] ABREU 95D give systematic errors ±0.0019 (model) and 0.0012 (R_c). We combine these in quadrature.

[32] BUSKULIC 94G uses e and μ events. This value is from a global fit to the lepton p and p_T (relative to jet) spectra which also determines the b and c production fractions, the fragmentation functions, and the forward-backward asymmetries. This branching ratio depends primarily on the ratio of dileptons to single leptons at high p_T, but the lower p_T portion of the lepton spectrum is included in the global fit to reduce the model dependence. The model dependence is ±0.0026 and is included in the systematic error.

[33] AKERS 93B analysis performed using single and dilepton events.

$\Gamma(e^+\nu_e\text{anything})/\Gamma_{\text{total}}$ $\qquad \Gamma_8/\Gamma$

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

The data in this block is included in the average printed for a previous datablock.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.109 ±0.005 OUR AVERAGE				
0.1089±0.0020±0.0051		[34,35] ACCIARRI 96C	L3	$e^+e^- \to Z$
0.107 ±0.015 ±0.007	260	[36] ABREU 93C	DLPH	$e^+e^- \to Z$
$0.109^{+0.014}_{-0.013}$ ±0.0055	2719	[37] AKERS 93B	OPAL	$e^+e^- \to Z$
0.138 ±0.032 ±0.008		[38] ADEVA 91C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.086 ±0.027 ±0.008		[39] ABE 93E	VNS	E^{ee}_{cm}= 58 GeV
0.111 ±0.028 ±0.026		BEHREND 90D	CELL	E^{ee}_{cm}= 43 GeV
0.150 ±0.011 ±0.022		BEHREND 90D	CELL	E^{ee}_{cm}= 35 GeV
0.112 ±0.009 ±0.011		ONG 88	MRK2	E^{ee}_{cm}= 29 GeV
$0.149^{+0.022}_{-0.019}$		PAL 86	DLCO	E^{ee}_{cm}= 29 GeV
0.110 ±0.018 ±0.010		AIHARA 85	TPC	E^{ee}_{cm}= 29 GeV
0.111 ±0.034 ±0.040		ALTHOFF 84J	TASS	E^{ee}_{cm}= 34.6 GeV
0.146 ±0.028		KOOP 84	DLCO	Repl. by PAL 86
0.116 ±0.021 ±0.017		NELSON 83	MRK2	E^{ee}_{cm}= 29 GeV

[34] ACCIARRI 96C result obtained by a fit to the single lepton spectrum.

[35] Assumes Standard Model value for R_B.

[36] ABREU 93C event count includes ee events. Combining ee, $\mu\mu$, and $e\mu$ events, they obtain 0.100 ± 0.007 ± 0.007.

[37] AKERS 93B analysis performed using single and dilepton events.

[38] ADEVA 91C measure the average $B(b \to eX)$ branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378 ± 3 MeV) for the decay of the Z into $b\overline{b}$, the electron result gives 0.112 ± 0.004 ± 0.008. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this electron result gives 370 ± 12 ± 24 MeV and combined with the muon result gives 385 ± 7 ± 22 MeV.

[39] ABE 93E experiment also measures forward-backward asymmetries and fragmentation functions for b and c.

$\Gamma(\mu^+\nu_\mu\text{anything})/\Gamma_{\text{total}}$ $\qquad \Gamma_9/\Gamma$

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

The data in this block is included in the average printed for a previous datablock.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.108 ±0.005 OUR AVERAGE				
0.1082±0.0015±0.0059		[40,41] ACCIARRI 96C	L3	$e^+e^- \to Z$
0.110 ±0.012 ±0.007	656	[42] ABREU 93C	DLPH	$e^+e^- \to Z$
$0.101^{+0.010}_{-0.009}$ ±0.0055	4248	[43] AKERS 93B	OPAL	$e^+e^- \to Z$
0.113 ±0.012 ±0.006		[44] ADEVA 91C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.122 ±0.006 ±0.007		[41] UENO 96	AMY	e^+e^- at 57.9 GeV
0.104 ±0.023 ±0.016		BEHREND 90D	CELL	E^{ee}_{cm}= 43 GeV
0.148 ±0.010 ±0.016		BEHREND 90D	CELL	E^{ee}_{cm}= 35 GeV
0.118 ±0.012 ±0.010		ONG 88	MRK2	E^{ee}_{cm}= 29 GeV
0.117 ±0.016 ±0.015		BARTEL 87	JADE	E^{ee}_{cm}= 34.6 GeV
0.114 ±0.018 ±0.025		BARTEL 85J	JADE	Repl. by BARTEL 87
0.117 ±0.028 ±0.010		ALTHOFF 84G	TASS	E^{ee}_{cm}= 34.5 GeV
0.105 ±0.015 ±0.013		ADEVA 83B	MRKJ	E^{ee}_{cm}= 33–38.5 GeV
$0.155^{+0.054}_{-0.029}$		FERNANDEZ 83D	MAC	E^{ee}_{cm}= 29 GeV

[40] ACCIARRI 96C result obtained by a fit to the single lepton spectrum.

[41] Assumes Standard Model value for R_B.

[42] ABREU 93C event count includes $\mu\mu$ events. Combining ee, $\mu\mu$, and $e\mu$ events, they obtain 0.100 ± 0.007 ± 0.007.

[43] AKERS 93B analysis performed using single and dilepton events.

[44] ADEVA 91C measure the average $B(b \to eX)$ branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378±3 MeV) for the decay of the Z into $b\overline{b}$, the muon result gives 0.123±0.003±0.006. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this muon result gives 394 ± 9 ± 22 MeV and combined with the electron result gives 385 ± 7 ± 22 MeV.

$\Gamma(D^- \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0202±0.0026±0.0013	[45] AKERS	95Q	OPAL	$e^+e^- \to Z$

[45] AKERS 95Q reports $[B(\overline{b} \to D^- \ell^+ \nu_\ell \text{anything}) \times B(D^+ \to K^- \pi^+ \pi^+)] = (1.82 \pm 0.20 \pm 0.12) \times 10^{-3}$. We divide by our best value $B(D^+ \to K^- \pi^+ \pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{D}^0 \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.065±0.006±0.001	[46] AKERS	95Q	OPAL	$e^+e^- \to Z$

[46] AKERS 95Q reports $[B(\overline{b} \to \overline{D}^0 \ell^+ \nu_\ell \text{anything}) \times B(D^0 \to K^- \pi^+)] = (2.52 \pm 0.14 \pm 0.17) \times 10^{-3}$. We divide by our best value $B(D^0 \to K^- \pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^{*-} \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0276±0.0027±0.0011	[47] AKERS	95Q	OPAL	$e^+e^- \to Z$

[47] AKERS 95Q reports $[B(\overline{b} \to D^* \ell^+ \nu_\ell X) \times B(D^{*+} \to D^0 \pi^+) \times B(D^0 \to K^- \pi^+)] = ((7.53 \pm 0.47 \pm 0.56) \times 10^{-4})$ and uses $B(D^{*+} \to D^0 \pi^+) = 0.681 \pm 0.013$ and $B(D^0 \to K^- \pi^+) = 0.0401 \pm 0.0014$ to obtain the above result. The first error is the experiments error and the second error is the systematic error from the D^{*+} and D^0 branching ratios.

$\Gamma(\overline{D}_J^0 \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{13}/Γ

D_J represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[48] AKERS	95Q	OPAL	$e^+e^- \to Z$

[48] AKERS 95Q quotes the product branching ratio $B(\overline{b} \to \overline{D}_J^0 \ell^+ \nu_\ell X)\, B(\overline{D}_J^0 \to D^{*+} \pi^-) = ((6.1 \pm 1.3 \pm 1.3) \times 10^{-3})$.

$\Gamma(D_J^- \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{14}/Γ

D_J represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[49] AKERS	95Q	OPAL	$e^+e^- \to Z$

[49] AKERS 95Q quotes the product branching ratio $B(\overline{b} \to D_J^- \ell^+ \nu_\ell \text{anything})\, B(D_J^- \to D^0 \pi^-) = ((7.0 \pm 1.9^{+1.2}_{-1.3}) \times 10^{-3})$.

$\Gamma(\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[50] AKERS	95Q	OPAL	$e^+e^- \to Z$

[50] AKERS 95Q quotes the product branching ratio $B(\overline{b} \to \overline{D}_2^*(2460)^0 \ell^+ \nu_\ell \text{anything})\, B(D_2^*(2460)^0 \to D^+ \pi^-) = (1.6 \pm 0.7 \pm 0.3) \times 10^{-3}$.

$\Gamma(D_2^*(2460)^- \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[51] AKERS	95Q	OPAL	$e^+e^- \to Z$

[51] AKERS 95Q quotes the product branching ratio $B(\overline{b} \to D_2^*(2460) \ell^+ \nu_\ell \text{anything})\, B(D_2^*(2460)^+ \to D^0 \pi^-) = 4.2 \pm 1.3^{+0.7}_{-1.2}$.

$\Gamma(\tau^+ \nu_\tau \text{anything})/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
2.6 ±0.4 OUR AVERAGE					
1.7 ±0.5 ±1.1		[52,53] ACCIARRI	96C	L3	$e^+e^- \to Z$
2.75±0.30±0.37	405	[54] BUSKULIC	95	ALEP	$e^+e^- \to Z$
2.4 ±0.7 ±0.8	1032	[55] ACCIARRI	94C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.08±0.76±0.62		BUSKULIC	93B	ALEP	Repl. by BUSKULIC 95

[52] ACCIARRI 96C result obtained from missing energy spectrum.

[53] Assumes Standard Model value for R_B.

[54] BUSKULIC 95 uses missing-energy technique.

[55] This is a direct result using tagged $b\overline{b}$ events at the Z, but species are not separated.

$\Gamma(\overline{b} \to \overline{c} \to \ell^- \overline{\nu}_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.078 ±0.006 OUR AVERAGE				
0.0770±0.0097±0.0046	[56] ABREU	95D	DLPH	$e^+e^- \to Z$
0.082 ±0.003 ±0.012	[57] BUSKULIC	94G	ALEP	$e^+e^- \to Z$
0.077 ±0.004 ±0.007	[58] AKERS	93B	OPAL	$e^+e^- \to Z$

[56] ABREU 95D give systematic errors ±0.0033 (model) and 0.0032 (R_c). We combine these in quadrature. This result is from the same global fit as their $\Gamma(\overline{b} \to \ell^+ \nu_\ell X)$ data.

[57] BUSKULIC 94G uses e and μ events. This value is from the same global fit as their $\Gamma(\overline{b} \to \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ data.

[58] AKERS 93B analysis performed using single and dilepton events.

$\Gamma(\overline{D}^0 \text{anything})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.601±0.029±0.014	[59] BUSKULIC	96Y	ALEP	$e^+e^- \to Z$

[59] BUSKULIC 96Y reports $0.605 \pm 0.024 \pm 0.016$ for $B(D^0 \to K^- \pi^+) = 0.0383$. We rescale to our best value $B(D^0 \to K^- \pi^+) = (3.85 \pm 0.09) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^- \text{anything})/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.237±0.017±0.015	[60] BUSKULIC	96Y	ALEP	$e^+e^- \to Z$

[60] BUSKULIC 96Y reports $0.234 \pm 0.013 \pm 0.010$ for $B(D^+ \to K^- \pi^+ \pi^+) = 0.091$. We rescale to our best value $B(D^+ \to K^- \pi^+ \pi^+) = (9.0 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{D}_s \text{anything})/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.02±0.04	[61] BUSKULIC	96Y	ALEP	$e^+e^- \to Z$

[61] BUSKULIC 96Y reports $0.183 \pm 0.019 \pm 0.009$ for $B(D_s^+ \to \phi \pi^+) = 0.036$. We rescale to our best value $B(D_s^+ \to \phi \pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(b \to \Lambda_c \text{anything})/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.097±0.013±0.025	[62] BUSKULIC	96Y	ALEP	$e^+e^- \to Z$

[62] BUSKULIC 96Y reports $0.110 \pm 0.014 \pm 0.006$ for $B(\Lambda_c^+ \to p K^- \pi^+) = 0.044$. We rescale to our best value $B(\Lambda_c^+ \to p K^- \pi^+) = (5.0 \pm 1.3) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{c}/c \text{anything})/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
1.17 ±0.04 OUR AVERAGE				
1.147±0.041	[63] ABREU	98D	DLPH	$e^+e^- \to Z$
1.230±0.036±0.065	[64] BUSKULIC	96Y	ALEP	$e^+e^- \to Z$

[63] ABREU 98D results are extracted from a fit to the b-tagging probability distribution based on the impact parameter.

[64] BUSKULIC 96Y assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons, and PDG 96 branching ratios for charm decays. This is sum of their inclusive $\overline{D}^0$, D^-, $\overline{D}_s$, and Λ_c branching ratios, corrected to include inclusive Ξ_c and charmonium.

$\Gamma(J/\psi(1S) \text{anything})/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.16±0.10 OUR AVERAGE						
1.12±0.12±0.10			[65] ABREU	94P	DLPH	$e^+e^- \to Z$
1.16±0.16±0.14		121	[66] ADRIANI	93J	L3	$e^+e^- \to Z$
1.21±0.13±0.08			BUSKULIC	92G	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.3 ±0.2 ±0.2			[67] ADRIANI	92	L3	$e^+e^- \to Z$
<4.9	90		MATTEUZZI	83	MRK2	E_{cm}^{ee}= 29 GeV

[65] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $J/\psi(1S) \to e^+e^-$ and $\mu^+\mu^-$ channels. Assumes $\Gamma(Z \to b\overline{b})/\Gamma_{\text{hadron}}$=0.22.

[66] ADRIANI 93J is an inclusive measurement from b decays at the Z. Uses $J/\psi(1S) \to \mu^+\mu^-$ and $J/\psi(1S) \to e^+e^-$ channels.

[67] ADRIANI 92 measurement is an inclusive result for $B(Z \to J/\psi(1S) X) = (4.1 \pm 0.7 \pm 0.3) \times 10^{-3}$ which is used to extract the b-hadron contribution to $J/\psi(1S)$ production.

$\Gamma(\psi(2S) \text{anything})/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0048±0.0022±0.0010	[68] ABREU	94P	DLPH	$e^+e^- \to Z$

[68] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$, $J/\psi(1S) \to \mu^+\mu^-$ channels. Assumes $\Gamma(Z \to b\overline{b})/\Gamma_{\text{hadron}}$=0.22.

$\Gamma(\chi_{c1}(1P) \text{anything})/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.018±0.005 OUR AVERAGE					
$0.014 \pm 0.006^{+0.004}_{-0.002}$		[69] ABREU	94P	DLPH	$e^+e^- \to Z$
0.024±0.009±0.002	19	[70] ADRIANI	93J	L3	$e^+e^- \to Z$

[69] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $\chi_{c1}(1P) \to J/\psi(1S)\gamma$, $J/\psi(1S) \to \mu^+\mu^-$ channels. Assumes no $\chi_{c2}(1P)$ and $\Gamma(Z \to b\overline{b})/\Gamma_{\text{hadron}}$=0.22.

[70] ADRIANI 93J is an inclusive measurement and assumes χ_{c1} come from b decays at Z. Uses $J/\psi(1S) \to \mu^+\mu^-$ channel.

$\Gamma(\chi_{c1}(1P) \text{anything})/\Gamma(J/\psi(1S) \text{anything})$ Γ_{26}/Γ_{24}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.92±0.82	121	[71] ADRIANI	93J	L3	$e^+e^- \to Z$

[71] ADRIANI 93J is a ratio of inclusive measurements from b decays at the Z using only the $J/\psi(1S) \to \mu^+\mu^-$ channel since some systematics cancel.

$\Gamma(\bar{s}\gamma)/\Gamma_{total}$ Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5.4 \times 10^{-4}$	90	[72] ADAM	96D	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0012	90	[73] ADRIANI	93L	L3	$e^+e^- \to Z$

[72] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

[73] ADRIANI 93L result is for $\bar{b} \to \bar{s}\gamma$ is performed inclusively.

$\Gamma(K^\pm \text{anything})/\Gamma_{total}$ Γ_{28}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.88\pm0.05\pm0.18$	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(K^0_S \text{anything})/\Gamma_{total}$ Γ_{29}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.290\pm0.011\pm0.027$	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(\pi^0 \text{anything})/\Gamma_{total}$ Γ_{30}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$2.78\pm0.15\pm0.60$	[74] ADAM	96	DLPH	$e^+e^- \to Z$

[74] ADAM 96 measurement obtained from a fit to the rapidity distribtuion of $\pi^{0's}$ in $Z \to b\,b$ events.

$\Gamma(p/\bar{p} \text{anything})/\Gamma_{total}$ Γ_{31}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.141\pm0.018\pm0.056$	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(\text{charged anything})/\Gamma_{total}$ Γ_{32}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$4.97\pm0.03\pm0.06$	[75] ABREU	98H	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$5.84\pm0.04\pm0.38$	ABREU	95C	DLPH	Repl. by ABREU 98H

[75] ABREU 98H measurement excludes the contribution from K^0 and Λ decay.

$\Gamma(\text{hadron}^+ \text{hadron}^-)/\Gamma_{total}$ Γ_{33}/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
$1.7^{+1.0}_{-0.7}\pm0.2$	[76,77] BUSKULIC	96V	ALEP	$e^+e^- \to Z$

[76] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[77] Average branching fraction of weakly decaying B hadrons into two long-lived charged hadrons, weighted by their production cross section and lifetimes.

$\Gamma(\text{charmless})/\Gamma_{total}$ Γ_{34}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.007 ± 0.021	[78] ABREU	98D	DLPH	$e^+e^- \to Z$

[78] ABREU 98D results are extracted from a fit to the b-tagging probabillity distribution based on the impact parameter. The expected hidden charm contribution of 0.026 ± 0.004 has been subtracted.

$\Gamma(\Lambda/\bar{\Lambda} \text{anything})/\Gamma_{total}$ Γ_{35}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.059 ± 0.006 OUR AVERAGE				
$0.0587\pm0.0046\pm0.0048$	ACKERSTAFF	97N	OPAL	$e^+e^- \to Z$
$0.059\pm0.007\pm0.009$	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(\mu^+\mu^- \text{anything})/\Gamma_{total}$ Γ_{37}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.2 \times 10^{-4}$	90	ABBOTT	98B	D0	$p\bar{p}$ 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.0 \times 10^{-5}$	90	[79] ALBAJAR	91C	UA1	$E^{p\bar{p}}_{cm} = 630$ GeV
<0.02	95	ALTHOFF	84G	TASS	$E^{ee}_{cm} = 34.5$ GeV
<0.007	95	ADEVA	83	MRKJ	$E^{ee}_{cm} = 30$–38 GeV
<0.007	95	BARTEL	83B	JADE	$E^{ee}_{cm} = 33$–37 GeV

[79] Both ABBOTT 98B and GLENN 98 claim that the efficiency quoted in ALBAJAR 91C was overestimated by a large factor.

$[\Gamma(e^+e^- \text{anything}) + \Gamma(\mu^+\mu^- \text{anything})]/\Gamma_{total}$ $(\Gamma_{36}+\Gamma_{37})/\Gamma$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.008	90	MATTEUZZI	83	MRK2	$E^{ee}_{cm} = 29$ GeV

$\Gamma(\nu\bar{\nu} \text{anything})/\Gamma_{total}$ Γ_{38}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.9 \times 10^{-4}$	[80] GROSSMAN	96	RVUE	$e^+e^- \to Z$

[80] GROSSMAN 96 limit is derived from the ALEPH BUSKULIC 95 limit $B(B^+ \to \tau^+\nu_\tau) < 1.8 \times 10^{-3}$ at CL=90% using conservative simplifying assumptions.

$B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE REFERENCES

ABBOTT	98B	PL B423 419	B. Abbott+	(D0 Collab.)
ABE	98B	PR D57 5382	F. Abe+	(CDF Collab.)
ABREU	98D	PL B426 193	P. Abreu+	(DELPHI Collab.)
ABREU	98H	PL B425 399	P. Abreu+	(DELPHI Collab.)
ACCIARRI	98	PL B416 220	M. Acciarri+	(L3 Collab.)
GLENN	98	PRL 80 2289	S. Glenn+	(CLEO Collab.)
ACKERSTAFF	97F	ZPHY C73 397	+Alexander, Allison, Ametewee+	(OPAL Collab.)
ACKERSTAFF	97N	ZPHY C74 423	K. Ackerstaff+	(OPAL Collab.)
ABREU	96E	PL B377 195	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	96C	ZPHY C71 379	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ADAM	96	ZPHY C69 561	+Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ADAM	96D	ZPHY C72 207	W. Adam+	(DELPHI Collab.)
BUSKULIC	96F	PL B369 151	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	96V	PL B384 471	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96Y	PL B388 648	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
GROSSMAN	96	NP B465 369	+Ligeti, Nardi	(REHO, CIT)
Also	96B	NP B480 753 (erratum)		
PDG	96	PR D54 1		
UENO	96	PL B381 365	+Kanda, Olsen, Kirk+	(AMY Collab.)
ABE,K	95B	PRL 75 3624	Abe, Abt, Ahn, Akagi+	(SLD Collab.)
ABREU	95C	PL B347 447	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95D	ZPHY C66 323	+Adam, Adye, Agasi+	(DELPHI Collab.)
ADAM	95	ZPHY C68 363	+Adye, Agasi, Ajinenko+	(DELPHI Collab.)
AKERS	95Q	ZPHY C67 57	+Alexander, Allison, Ametewee+	(OPAL Collab.)
BUSKULIC	95	PL B343 444	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
ABREU	94L	ZPHY C63 3	+Adam, Adye, Agasi, Aleksan+	(DELPHI Collab.)
ABREU	94P	PL B341 109	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	94C	PL B332 201	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
BUSKULIC	94G	ZPHY C62 179	+Casper, De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABE	93E	PL B313 288	+Amako, Arai, Arima, Asano+	(VENUS Collab.)
ABE	93J	PRL 71 3421	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABREU	93C	PL B301 145	+Adam, Adye, Agasi, Aleksan+	(DELPHI Collab.)
ABREU	93D	ZPHY C57 181	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	93G	PL B312 253	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACTON	93C	PL B307 247	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ACTON	93L	ZPHY C60 217	+Akers, Alexander, Allison, Anderson+	(OPAL Collab.)
ADRIANI	93J	PL B317 467	+Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
ADRIANI	93K	PL B317 474	+Aguilar-Benitez, Ahlen, Alcarez+	(L3 Collab.)
ADRIANI	93L	PL B317 637	+Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
AKERS	93B	ZPHY C60 199	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
BUSKULIC	93B	PL B298 479	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	93O	PL B314 459	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
ABREU	92	ZPHY C53 567	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	92	PL B274 513	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADRIANI	92	PL B288 412	+Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
BUSKULIC	92F	PL B295 174	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	92G	PL B295 396	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
ADEVA	91C	PL B261 177	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	91H	PL B270 111	+Adrani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ALBAJAR	91C	PL B262 163	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALEXANDER	91G	PL B266 485	+Allison, Allport+	(OPAL Collab.)
DECAMP	91C	PL B257 492	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
BEHREND	90D	ZPHY C47 333	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
HAGEMANN	90	ZPHY C48 401	+Ramcke, Allison, Ambrus, Barlow+	(JADE Collab.)
LYONS	90	PR D41 982	+Martin, Saxon	(OXF, BRIS, RAL)
BRAUNSCH...	89B	ZPHY C44 1	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ONG	89	PRL 62 1236	+Jaros, Abrams, Amidei, Baden+	(Mark II Collab.)
KLEM	88	PR D37 41	+Atwood, Barish+	(DELCO Collab.)
ONG	88	PRL 60 2587	+Weir, Abrams, Amidei+	(Mark II Collab.)
ASH	87	PRL 58 640	+Band, Bloom, Bosman+	(MAC Collab.)
BARTEL	87	ZPHY C33 339	+Becker, Felst, Haidt+	(JADE Collab.)
BROM	87	PL B195 301	+Abachi, Akerlof, Baringer+	(HRS Collab.)
PAL	86	PR D33 2708	+Atwood, Barish, Bonneaud+	(DELCO Collab.)
AIHARA	85	ZPHY C27 39	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
BARTEL	85J	PL 163B 277	+Becker, Cords, Felst+	(JADE Collab.)
ALTHOFF	84G	ZPHY C22 219	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84J	PL 146B 443	+Branschweig, Kirschfink+	(TASSO Collab.)
KOOP	84	PRL 52 970	+Sakuda, Atwood, Baillon+	(DELCO Collab.)
ADEVA	83	PRL 50 799	+Barber, Becker, Berdugo+	(Mark-J Collab.)
ADEVA	83B	PRL 51 443	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BARTEL	83B	PL 132B 241	+Becker, Bowdery, Cords+	(JADE Collab.)
FERNANDEZ	83D	PRL 50 2054	+Ford, Read, Smith+	(MAC Collab.)
MATTEUZZI	83	PL 129B 141	+Abrams, Amidei, Blocker+	(Mark II Collab.)
NELSON	83	PRL 50 1542	+Blondel, Trilling, Abrams+	(Mark II Collab.)

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

B^* MASS

From mass difference below and the average of our B masses $(m_{B^\pm}+m_{B^0})/2$.

VALUE (MeV)	DOCUMENT ID
5324.9 ± 1.8 OUR FIT	

$m_{B^*} - m_B$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
45.78 ± 0.35 OUR FIT					
45.78 ± 0.35 OUR AVERAGE					
$46.2\pm0.3\pm0.8$		[1] ACKERSTAFF	97M	OPAL	$e^+e^- \to Z$
$45.3\pm0.35\pm0.87$	4227	[1] BUSKULIC	96D	ALEP	$E^{ee}_{cm} = 88$–94 GeV
$45.5\pm0.3\pm0.8$		[1] ABREU	95R	DLPH	$E^{ee}_{cm} = 88$–94 GeV
46.3 ± 1.9	1378	[1] ACCIARRI	95B	L3	$E^{ee}_{cm} = 88$–94 GeV
$46.4\pm0.3\pm0.8$		[2] AKERIB	91	CLE2	$e^+e^- \to \gamma X$
45.6 ± 0.8		[2] WU	91	CSB2	$e^+e^- \to \gamma X, \gamma \ell X$
45.4 ± 1.0		[3] LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$52\pm2\pm4$	1400	[4] HAN	85	CUSB	$e^+e^- \to \gamma e X$

[1] u, d, s flavor averaged.

[2] These papers report E_γ in the B^* center of mass. The $m_{B^*} - m_B$ is 0.2 MeV higher. E_{cm} = 10.61–10.7 GeV. Admixture of B^0 and B^+ mesons, but not B_s.

[3] LEE-FRANZINI 90 value is for an admixture of B^0 and B^+. They measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s, and use the shape of the photon line to separate the above value.

[4] HAN 85 is for E_{cm} = 10.6–11.2 GeV, giving an admixture of B^0, B^+, and B_s.

$|(m_{B^{*+}} - m_{B^+}) - (m_{B^{*0}} - m_{B^0})|$

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<6	95	ABREU 95R	DLPH	E_{cm}^{ee} = 88–94 GeV

B^* DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B\gamma$	dominant

B^* REFERENCES

ACKERSTAFF	97M	ZPHY C74 413	K. Ackerstaff+	(OPAL Collab.)
BUSKULIC	96D	ZPHY C69 393	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABREU	95R	ZPHY C68 353	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	95B	PL B345 589	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERIB	91	PRL 67 1692	+Barish, Cown, Eigen, Stroynowski+	(CLEO Collab.)
WU	91	PL B273 177	+Franzini, Kanekal, Tuts+	(CUSB II Collab.)
LEE-FRANZINI	90	PRL 65 2947	+Heintz, Lovelock, Narain, Schamberger+	(CUSB II Collab.)
HAN	85	PRL 55 36	+Klopfenstein, Mageras+	(COLU, LSU, MPIM, STON)

$B_J^*(5732)$

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

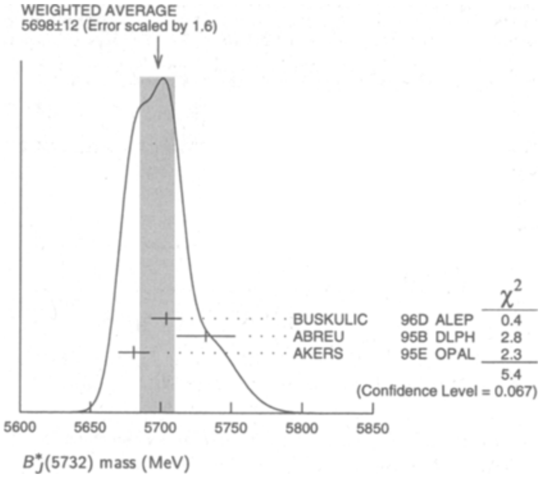
OMITTED FROM SUMMARY TABLE

Signal can be interpreted as stemming from several narrow and broad resonances. Needs confirmation.

$B_J^*(5732)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5698±12 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
5704± 4±10	1944	[1] BUSKULIC 96D	ALEP	E_{cm}^{ee} = 88–94 GeV
5732± 5±20	2157	ABREU 95B	DLPH	E_{cm}^{ee} = 88–94 GeV
5681±11	1738	AKERS 95E	OPAL	E_{cm}^{ee} = 88–94 GeV

[1] Using $m_{B\pi} - m_B = 424 \pm 4 \pm 10$ MeV.



$B_J^*(5732)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
128±18 OUR AVERAGE				
145±28	2157	ABREU 95B	DLPH	E_{cm}^{ee} = 88–94 GeV
116±24	1738	AKERS 95E	OPAL	E_{cm}^{ee} = 88–94 GeV

$B_J^*(5732)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B^*\pi + B\pi$	dominant

$B_J^*(5732)$ REFERENCES

BUSKULIC	96D	ZPHY C69 393	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABREU	95B	PL B345 598	+	(DELPHI Collab.)
AKERS	95E	ZPHY C66 19	+Alexander, Allison+	(OPAL Collab.)

BOTTOM, STRANGE MESONS
$(B = \pm1,\ S = \mp1)$

$B_s^0 = s\overline{b}$, $\overline{B}_s^0 = \overline{s}b$, similarly for B_s^*'s

B_s^0

$I(J^P) = 0(0^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

B_s^0 MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B_s^0}$, and $(m_{B_s^0} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B_s^0}$, and the mass differences.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5369.3± 2.0 OUR FIT					
5369.6± 2.4 OUR AVERAGE					
5369.9± 2.3±1.3	32	[1] ABE	96B	CDF	$p\overline{p}$ at 1.8 TeV
5374 ±16 ±2	3	ABREU	94D	DLPH	$e^+e^- \rightarrow Z$
5359 ±19 ±7	1	[1] AKERS	94J	OPAL	$e^+e^- \rightarrow Z$
5368.6± 5.6±1.5	2	BUSKULIC	93G	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5370 ±40	6	[2] AKERS	94J	OPAL	$e^+e^- \rightarrow Z$
5383.3± 4.5±5.0	14	ABE	93F	CDF	Repl by ABE 96B

[1] From the decay $B_s \rightarrow J/\psi(1S)\phi$.

[2] From the decay $B_s \rightarrow D_s^- \pi^+$.

$m_{B_s^0} - m_B$

m_B is the average of our B masses $(m_{B^\pm}+m_{B^0})/2$. The fits uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B_s^0}$, and $m_{B_s^0} - m_B$ to determine m_{B^+}, m_{B^0}, $m_{B_s^0}$, and the mass differences.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
90.2±2.2 OUR FIT					
89.7±2.7±1.2		ABE	96B	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
80 to 130	68	LEE-FRANZINI	90	CSB2	$e^+e^- \rightarrow \Upsilon(5S)$

$m_{B_{sH}^0} - m_{B_{sL}^0}$

See the B_s^0-$\overline{B}_s^0$ MIXING section near the end of these B_s^0 Listings.

B_s^0 MEAN LIFE

"OUR EVALUATION" is an average of the data listed below performed by the LEP *B* Lifetimes Working Group as described in our review "Production and Decay of *b*-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.54±0.07 OUR EVALUATION					
$1.34^{+0.23}_{-0.19}\pm0.05$		[3] ABE	98B	CDF	$p\overline{p}$ at 1.8 TeV
$1.72^{+0.20}_{-0.19}{}^{+0.18}_{-0.17}$		[4] ACKERSTAFF	98F	OPAL	$e^+e^- \rightarrow Z$
$1.50^{+0.16}_{-0.15}\pm0.04$		[5] ACKERSTAFF	98G	OPAL	$e^+e^- \rightarrow Z$
$1.47\pm0.14\pm0.08$		[6] BARATE	98C	ALEP	$e^+e^- \rightarrow Z$
$1.56^{+0.29}_{-0.26}{}^{+0.08}_{-0.07}$		[5] ABREU	96F	DLPH	$e^+e^- \rightarrow Z$
$1.65^{+0.34}_{-0.31}\pm0.12$		[6] ABREU	96F	DLPH	$e^+e^- \rightarrow Z$
$1.76\pm0.20^{+0.15}_{-0.10}$		[7] ABREU	96F	DLPH	$e^+e^- \rightarrow Z$
$1.60\pm0.26^{+0.13}_{-0.15}$		[8] ABREU	96F	DLPH	$e^+e^- \rightarrow Z$
$1.54^{+0.14}_{-0.13}\pm0.04$		[5] BUSKULIC	96M	ALEP	$e^+e^- \rightarrow Z$
$1.42^{+0.27}_{-0.23}\pm0.11$	76	[5] ABE	95R	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.51 ± 0.11		[9] BARATE	98C	ALEP	$e^+e^- \rightarrow Z$
$1.34^{+0.23}_{-0.19}\pm0.05$		[10] ABE	96N	CDF	Repl. by ABE 98B
1.67 ± 0.14		[11] ABREU	96F	DLPH	$e^+e^- \rightarrow Z$
$1.61^{+0.30}_{-0.29}{}^{+0.18}_{-0.16}$	90	[6] BUSKULIC	96E	ALEP	Repl. by BARATE 98C
$1.74^{+1.08}_{-0.69}\pm0.07$	8	[12] ABE	95R	CDF	Sup. by ABE 96N
$1.54^{+0.25}_{-0.21}\pm0.06$	79	[5] AKERS	95G	OPAL	Repl. by ACKER-STAFF 98G
$1.59^{+0.17}_{-0.15}\pm0.03$	134	[5] BUSKULIC	95O	ALEP	Sup. by BUSKULIC 96M
0.96 ± 0.37	41	[13] ABREU	94E	DLPH	Sup. by ABREU 96F
$1.92^{+0.45}_{-0.35}\pm0.04$	31	[5] BUSKULIC	94C	ALEP	Sup. by BUSKULIC 95O
$1.13^{+0.35}_{-0.26}\pm0.09$	22	[5] ACTON	93H	OPAL	Sup. by AKERS 95G

[3] Measured using fully reconstructed $B_s \rightarrow J/\psi(1S)\phi$ decay.

[4] ACKERSTAFF 98F use fully reconstructed $D_s^- \rightarrow \phi\pi^-$ and $D_s^- \rightarrow K^{*0}K^-$ in the inclusive B_s^0 decay.

[5] Measured using $D_s^- \ell^+$ vertices.

[6] Measured using D_s hadron vertices.

[7] Measured using $\phi\ell$ vertices.

[8] Measured using inclusive D_s vertices.

[9] Combined results from $D_s^- \ell^+$ and D_s hadron.

[10] ABE 96N uses 58 ± 12 exclusive $B_s \rightarrow J/\psi(1S)\phi$ events.

[11] Combined result for the four ABREU 96F methods.

[12] Exclusive reconstruction of $B_s \rightarrow \psi\phi$.

[13] ABREU 94E uses the flight-distance distribution of D_s vertices, ϕ-lepton vertices, and $D_s\mu$ vertices.

B_s^0 DECAY MODES

These branching fractions all scale with $B(\overline{b} \rightarrow B_s^0)$, the LEP B_s^0 production fraction. The first four were evaluated using $B(\overline{b} \rightarrow B_s^0) = (10.5^{+1.8}_{-1.7})\%$ and the rest assume $B(\overline{b} \rightarrow B_s^0) = 12\%$.

The branching fraction $B(B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell \text{anything})$ is not a pure measurement since the measured product branching fraction $B(\overline{b} \rightarrow B_s^0) \times B(B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell \text{anything})$ was used to determine $B(\overline{b} \rightarrow B_s^0)$, as described in the note on "Production and Decay of *b*-Flavored Hadrons."

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	D_s^- anything	(92 ±33) %	
Γ_2	$D_s^- \ell^+ \nu_\ell$ anything	[a] (8.1 ± 2.5) %	
Γ_3	$D_s^- \pi^+$	< 13 %	
Γ_4	$J/\psi(1S)\phi$	(9.3 ± 3.3) × 10^{-4}	
Γ_5	$J/\psi(1S)\pi^0$	< 1.2 × 10^{-3}	90%
Γ_6	$J/\psi(1S)\eta$	< 3.8 × 10^{-3}	90%
Γ_7	$\psi(2S)\phi$	seen	
Γ_8	$\pi^+\pi^-$	< 1.7 × 10^{-4}	90%
Γ_9	$\pi^0\pi^0$	< 2.1 × 10^{-4}	90%
Γ_{10}	$\eta\pi^0$	< 1.0 × 10^{-3}	90%
Γ_{11}	$\eta\eta$	< 1.5 × 10^{-3}	90%
Γ_{12}	π^+K^-	< 2.1 × 10^{-4}	90%
Γ_{13}	K^+K^-	< 5.9 × 10^{-5}	90%
Γ_{14}	$p\overline{p}$	< 5.9 × 10^{-5}	90%
Γ_{15}	$\gamma\gamma$	< 1.48 × 10^{-4}	90%
Γ_{16}	$\phi\gamma$	< 7 × 10^{-4}	90%

Lepton Family number (*LF*) violating modes or
$\Delta B = 1$ weak neutral current (*B1*) modes

Γ_{17}	$\mu^+\mu^-$	*B1*	< 2.0 × 10^{-6}	90%
Γ_{18}	e^+e^-	*B1*	< 5.4 × 10^{-5}	90%
Γ_{19}	$e^\pm\mu^\mp$	*LF*	[b] < 4.1 × 10^{-5}	90%
Γ_{20}	$\phi\nu\overline{\nu}$	*B1*	< 5.4 × 10^{-3}	90%

[a] Not a pure measurement. See note at head of B_s^0 Decay Modes.

[b] The value is for the sum of the charge states of particle/antiparticle states indicated.

B_s^0 BRANCHING RATIOS

$\Gamma(D_s^- \text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.92±0.33 OUR AVERAGE					
0.81±0.24±0.24	90	[14] BUSKULIC	96E	ALEP	$e^+e^- \to Z$
1.56±0.58±0.47	147	[15] ACTON	92N	OPAL	$e^+e^- \to Z$

[14] BUSKULIC 96E separate $c\overline{c}$ and $b\overline{b}$ sources of D_s^+ mesons using a lifetime tag, subtract generic $\overline{b} \to W^+ \to D_s^+$ events, and obtain $B(\overline{b} \to B_s^0) \times B(B_s^0 \to D_s^-\text{anything}) = 0.088 \pm 0.020 \pm 0.020$ assuming $B(D_s \to \phi\pi) = (3.5 \pm 0.4) \times 10^{-2}$ and PDG 1994 values for the relative partial widths to other D_s channels. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$.

[15] ACTON 92N assume that excess of 147 ± 48 D_s^0 events over that expected from B^0, B^+, and $c\overline{c}$ is all from B_s^0 decay. The product branching fraction is measured to be $B(\overline{b} \to B_s^0)B(B_s^0 \to D_s^-\text{anything}) \times B(D_s^- \to \phi\pi^-) = (5.9 \pm 1.9 \pm 1.1) \times 10^{-3}$. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$.

$\Gamma(D_s^- \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_2/Γ

The values and averages in this section serve only to show what values result if one assumes our $B(\overline{b} \to B_s^0)$. They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine $B(\overline{b} \to B_s^0)$ as described in the note on "Production and Decay of *b*-Flavored Hadrons."

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.081±0.025 OUR AVERAGE					
0.076±0.012±0.022	134	[16] BUSKULIC	95O	ALEP	$e^+e^- \to Z$
0.107±0.043±0.032		[17] ABREU	92M	DLPH	$e^+e^- \to Z$
0.103±0.036±0.031	18	[18] ACTON	92N	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.13 ±0.04 ±0.04	27	[19] BUSKULIC	92E	ALEP	$e^+e^- \to Z$

[16] BUSKULIC 95O use $D_s \ell$ correlations. The measured product branching ratio is $B(\overline{b} \to B_s) \times B(B_s \to D_s^- \ell^+ \nu_\ell \text{anything}) = (0.82 \pm 0.09^{+0.13}_{-0.14})\%$ assuming $B(D_s \to \phi\pi) = (3.5 \pm 0.4) \times 10^{-2}$ and PDG 1994 values for the relative partial widths to the six other D_s channels used in this analysis. Combined with results from $\Upsilon(4S)$ experiments this can be used to extract $B(\overline{b} \to B_s) = (11.0 \pm 1.2^{+2.5}_{-2.6})\%$. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$.

[17] ABREU 92M measured muons only and obtained product branching ratio $B(Z \to b \text{ or } \overline{b}) \times B(\overline{b} \to B_s) \times B(B_s \to D_s \mu^+ \nu_\mu \text{anything}) \times B(D_s \to \phi\pi) = (18 \pm 8) \times 10^{-5}$. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$. We use $B(Z \to b \text{ or } \overline{b}) = 2B(Z \to b\overline{b}) = 2\times(0.2212 \pm 0.0019)$.

[18] ACTON 92N is measured using $D_s \to \phi\pi^+$ and $K^*(892)^0 K^+$ events. The product branching fraction measured is measured to be $B(\overline{b} \to B_s^0)B(B_s^0 \to D_s^- \ell^+ \nu_\ell \text{anything}) \times B(D_s^- \to \phi\pi^-) = (3.9 \pm 1.1 \pm 0.8) \times 10^{-4}$. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$.

[19] BUSKULIC 92E is measured using $D_s \to \phi\pi^+$ and $K^*(892)^0 K^+$ events. They use 2.7 ± 0.7% for the $\phi\pi^+$ branching fraction. The average product branching fraction is measured to be $B(\overline{b} \to B_s^0)B(B_s^0 \to D_s^- \ell^+ \nu_\ell \text{anything}) = 0.020 \pm 0.0055^{+0.005}_{-0.006}$. We evaluate using our current values $B(\overline{b} \to B_s^0) = 0.105^{+0.018}_{-0.017}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B_s^0)$ and $B(D_s \to \phi\pi)$. Superseded by BUSKULIC 95O.

$\Gamma(D_s^- \pi^+)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.13	6	[20] AKERS	94J	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	1	BUSKULIC	93G	ALEP	$e^+e^- \to Z$

[20] AKERS 94J sees ≤ 6 events and measures the limit on the product branching fraction $f(\overline{b} \to B_s^0) \cdot B(B_s^0 \to D_s^- \pi^+) < 1.3\%$ at CL = 90%. We divide by our current value $B(\overline{b} \to B_s^0) = 0.105$.

$\Gamma(J/\psi(1S)\phi)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.93±0.28±0.17		[21] ABE	96Q	CDF	$p\overline{p}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6	1	[22] AKERS	94J	OPAL	$e^+e^- \to Z$
seen	14	[23] ABE	93F	CDF	$p\overline{p}$ at 1.8 TeV
seen	1	[24] ACTON	92N	OPAL	Sup. by AKERS 94J

[21] ABE 96Q assumes $f_u = f_d$ and $f_s/f_u = 0.40 \pm 0.06$. Uses $B \to J/\psi(1S)K$ and $B \to J/\psi(1S)K^*$ branching fractions from PDG 94. They quote two systematic errors, ±0.10 and ±0.14 where the latter is the uncertainty in f_s. We combine in quadrature.

[22] AKERS 94J sees one event and measures the limit on the product branching fraction $f(\overline{b} \to B_s^0) \cdot B(B_s^0 \to J/\psi(1S)\phi) < 7 \times 10^{-4}$ at CL = 90%. We divide by our current value $B(\overline{b} \to B_s^0) = 0.112$.

[23] ABE 93F measured using $J/\psi(1S) \to \mu^+\mu^-$ and $\phi \to K^+K^-$.

[24] In ACTON 92N a limit on the product branching fraction is measured to be $f(\overline{b} \to B_s^0) \cdot B(B_s^0 \to J/\psi(1S)\phi) \le 0.22 \times 10^{-2}$.

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN
<1.2 × 10^{-3}	90	[25] ACCIARRI	97C	L3

[25] ACCIARRI 97C assumes B^0 production fraction (39.5 ± 4.0%) and B_s (12.0 ± 3.0%).

$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN
<3.8 × 10^{-3}	90	[26] ACCIARRI	97C	L3

[26] ACCIARRI 97C assumes B^0 production fraction (39.5 ± 4.0%) and B_s (12.0 ± 3.0%).

$\Gamma(\psi(2S)\phi)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	BUSKULIC	93G	ALEP	$e^+e^- \to Z$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 × 10^{-4}	90	[27] BUSKULIC	96V	ALEP	$e^+e^- \to Z$

[27] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, *b* baryons.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10^{-4}	90	[28] ACCIARRI	95H	L3	$e^+e^- \to Z$

[28] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.0 × 10^{-3}	90	[29] ACCIARRI	95H	L3	$e^+e^- \to Z$

[29] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.5 × 10^{-3}	90	[30] ACCIARRI	95H	L3	$e^+e^- \to Z$

[30] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\pi^+K^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10^{-4}	90	[31] BUSKULIC	96V	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6 × 10^{-4}	90	[32] AKERS	94L	OPAL	$e^+e^- \to Z$

[31] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, *b* baryons.

[32] Assumes $B(Z \to b\overline{b}) = 0.217$ and B_d^0 (B_s^0) fraction 39.5% (12%).

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.9 × 10^{-5}	90	[33] BUSKULIC	96V	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4 × 10^{-4}	90	[34] AKERS	94L	OPAL	$e^+e^- \to Z$

[33] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, *b* baryons.

[34] Assumes $B(Z \to b\overline{b}) = 0.217$ and B_d^0 (B_s^0) fraction 39.5% (12%).

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.9 × 10^{-5}	90	[35] BUSKULIC	96V	ALEP	$e^+e^- \to Z$

[35] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, *b* baryons.

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<14.8 × 10^{-5}	90	[36] ACCIARRI	95I	L3	$e^+e^- \to Z$

[36] ACCIARRI 95I assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\phi\gamma)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-4}	90	[37] ADAM	96D	DLPH	$e^+e^- \to Z$

[37] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.0 \times 10^{-6}$	90	[38] ABE 98	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.8 \times 10^{-5}$	90	[39] ACCIARRI 97B	L3	$e^+e^- \to Z$
$<8.4 \times 10^{-6}$	90	[40] ABE 96L	CDF	Repl. by ABE 98

[38] ABE 98 assumes production of $\sigma(B^0) = \sigma(B^+)$ and $\sigma(B_s)/\sigma(B^0) = 1/3$. They normalize to their measured $\sigma(B^0, p_T(B) > 6, |y| < 1.0) = 2.39 \pm 0.32 \pm 0.44\,\mu$b.

[39] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.

[40] ABE 96L assumes B^+/B_s production ratio 3/1. They normalize to their measured $\sigma(B^+, p_T(B) > 6$ GeV/c, $|y| < 1) = 2.39 \pm 0.54\,\mu$b.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{18}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.4 \times 10^{-5}$	90	[41] ACCIARRI 97B	L3	$e^+e^- \to Z$

[41] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\text{total}}$ Γ_{19}/Γ

test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.1 \times 10^{-5}$	90	[42] ACCIARRI 97B	L3	$e^+e^- \to Z$

[42] ACCIARRI 97B assume PDG 96 production fractions for B^+, B^0, B_s, and Λ_b.

$\Gamma(\phi\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_{20}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.4 \times 10^{-3}$	90	[43] ADAM 96D	DLPH	$e^+e^- \to Z$

[43] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

POLARIZATION IN B^0_s DECAY

Γ_L/Γ in $B^0_s \to J/\psi(1S)\phi$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.56 \pm 0.21^{+0.02}_{-0.04}$	19	ABE 95Z	CDF	$p\overline{p}$ at 1.8 TeV

B^0_s-$\overline{B}^0_s$ MIXING

For a discussion of B^0_s-$\overline{B}^0_s$ mixing see the note on "B^0-$\overline{B}^0$ Mixing" in the B^0 Particle Listings above.

χ_s is a measure of the time-integrated B^0_s-$\overline{B}^0_s$ mixing probability that produced $B^0_s(\overline{B}^0_s)$ decays as a $\overline{B}^0_s(B^0_s)$. Mixing violates $\Delta B \neq 2$ rule.

$$\chi_s = \frac{x_s^2}{2(1+x_s^2)}$$

$$x_s = \frac{\Delta m_{B^0_s}}{\Gamma_{B^0_s}} = (m_{B^0_{sH}} - m_{B^0_{sL}})\,\tau_{B^0_s},$$

where H, L stand for heavy and light states of two B^0_s CP eigenstates and $\tau_{B^0_s} = \frac{1}{0.5(\Gamma_{B^0_{sH}} + \Gamma_{B^0_{sL}})}$.

χ_B at high energy

This is a B-$\overline{B}$ mixing measurement for an admixture of B^0 and B^0_s at high energy.

$\chi_B = f'_d\chi_d + f'_s\chi_s$

where f'_d and f'_s are the branching ratio times production fractions of B^0_d and B^0_s mesons relative to all b-flavored hadrons which decay weakly. Mixing violates $\Delta B \neq 2$ rule.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.118 ± 0.006 OUR AVERAGE					
$0.131 \pm 0.020 \pm 0.016$			[44] ABE 97I	CDF	$p\overline{p}$ 1.8 TeV
$0.1107 \pm 0.0062 \pm 0.0055$			[45] ALEXANDER 96	OPAL	$e^+e^- \to Z$
$0.121 \pm 0.016 \pm 0.006$			[46] ABREU 94J	DLPH	$e^+e^- \to Z$
$0.123 \pm 0.012 \pm 0.008$			ACCIARRI 94D	L3	$e^+e^- \to Z$
$0.114 \pm 0.014 \pm 0.008$			[47] BUSKULIC 94G	ALEP	$e^+e^- \to Z$
0.129 ± 0.022			[48] BUSKULIC 92B	ALEP	$e^+e^- \to Z$
$0.176 \pm 0.031 \pm 0.032$		1112	[49] ABE 91G	CDF	$p\overline{p}$ 1.8 TeV
$0.148 \pm 0.029 \pm 0.017$			[50] ALBAJAR 91D	UA1	$p\overline{p}$ 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.136 \pm 0.037 \pm 0.040$			[51] UENO 96	AMY	e^+e^- at 57.9 GeV
$0.144 \pm 0.014\ ^{+0.017}_{-0.011}$			[52] ABREU 94F	DLPH	Sup. by ABREU 94J
0.131 ± 0.014			[53] ABREU 94J	DLPH	$e^+e^- \to Z$
$0.157 \pm 0.020 \pm 0.032$			[54] ALBAJAR 94	UA1	$\sqrt{s} = 630$ GeV
$0.121\ ^{+0.044}_{-0.040} \pm 0.017$		1665	[55] ABREU 93C	DLPH	Sup. by ABREU 94J
$0.143\ ^{+0.022}_{-0.021} \pm 0.007$			[56] AKERS 93B	OPAL	Sup. by ALEXANDER 96
$0.145\ ^{+0.041}_{-0.035} \pm 0.018$			[57] ACTON 92C	OPAL	$e^+e^- \to Z$
$0.121 \pm 0.017 \pm 0.006$			[58] ADEVA 92C	L3	Sup. by ACCIARRI 94D
$0.132 \pm 0.22\ ^{+0.015}_{-0.012}$		823	[59] DECAMP 91	ALEP	$e^+e^- \to Z$
$0.178\ ^{+0.049}_{-0.040} \pm 0.020$			[60] ADEVA 90P	L3	$e^+e^- \to Z$
$0.17\ ^{+0.15}_{-0.08}$			[61,62] WEIR 90	MRK2	e^+e^- 29 GeV
$0.21\ ^{+0.29}_{-0.15}$			[61] BAND 88	MAC	$E^{ee}_{\text{cm}} = 29$ GeV
>0.02	90		[61] BAND 88	MAC	$E^{ee}_{\text{cm}} = 29$ GeV
0.121 ± 0.047			[61,63] ALBAJAR 87C	UA1	Repl. by ALBAJAR 91D
<0.12	90		[61,64] SCHAAD 85	MRK2	$E^{ee}_{\text{cm}} = 29$ GeV

[44] Uses di-muon events.

[45] ALEXANDER 96 uses a maximum likelihood fit to simultaneously extract χ as well as the forward-backward asymmetries in $e^+e^- \to Z \to b\overline{b}$ and $c\overline{c}$.

[46] This ABREU 94J result is from 5182 $\ell\ell$ and 279 $\Lambda\ell$ events. The systematic error includes 0.004 for model dependence.

[47] BUSKULIC 94G data analyzed using ee, $e\mu$, and $\mu\mu$ events.

[48] BUSKULIC 92B uses a jet charge technique combined with electrons and muons.

[49] ABE 91G measurement of χ is done with $e\mu$ and ee events.

[50] ALBAJAR 91D measurement of χ is done with dimuons.

[51] UENO 96 extracted χ from the energy dependence of the forward-backward asymmetry.

[52] ABREU 94F uses the average electric charge sum of the jets recoiling against a b-quark jet tagged by a high p_T muon. The result is for $\overline{\chi} = f_d\chi_d + 0.9 f_s\chi_s$.

[53] This ABREU 94J result combines $\ell\ell$, $\Lambda\ell$, and jet-charge ℓ (ABREU 94F) analyses. It is for $\overline{\chi} = f_d\chi_d + 0.96 f_s\chi_s$.

[54] ALBAJAR 94 uses dimuon events. Not independent of ALBAJAR 91D.

[55] ABREU 93C data analyzed using ee, $e\mu$, and $\mu\mu$ events.

[56] AKERS 93B analysis performed using dilepton events.

[57] ACTON 92C uses electrons and muons. Superseded by AKERS 93B.

[58] ADEVA 92C uses electrons and muons.

[59] DECAMP 91 done with opposite and like-sign dileptons. Superseded by BUSKULIC 92B.

[60] ADEVA 90P measurement uses ee, $\mu\mu$, and $e\mu$ events from 118k events at the Z. Superseded by ADEVA 92C.

[61] These experiments are not in the average because the combination of B_s and B_d mesons which they see could differ from those at higher energy.

[62] The WEIR 90 measurement supersedes the limit obtained in SCHAAD 85. The 90% CL are 0.06 and 0.38.

[63] ALBAJAR 87C measured $\chi = (\overline{B}^0 \to B^0 \to \mu^+ X)$ divided by the average production weighted semileptonic branching fraction for B hadrons at 546 and 630 GeV.

[64] Limit is average probability for hadron containing B quark to produce a positive lepton.

$\Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}}$

$\Delta m_{B^0_s}$ is a measure of 2π times the B^0_s-$\overline{B}^0_s$ oscillation frequency in time-dependent mixing experiments.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Oscillation Working Group as described in our review "Production and Decays of B-flavored Hadrons" in the $B^\pm$ Section of these Listings. The averaging procedure takes into account correlations between the measurements.

VALUE (10^{12} $\hbar$ s^{-1})	CL%	DOCUMENT ID	TECN	COMMENT
>9.1 (CL = 95%) OUR EVALUATION				
>7.9	95	[65] BARATE 98C	ALEP	$e^+e^- \to Z$
>3.1	95	[66] ACKERSTAFF 97U	OPAL	$e^+e^- \to Z$
>6.5	95	[67] ADAM 97	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>2.2	95	[68] ACKERSTAFF 97V	OPAL	$e^+e^- \to Z$
>6.6	95	[69] BUSKULIC 96M	ALEP	Repl. by BARATE 98C
>2.2	95	[68] AKERS 95J	OPAL	Sup. by ACKERSTAFF 97V
>5.7	95	[70] BUSKULIC 95J	ALEP	$e^+e^- \to Z$
>1.8	95	[68] BUSKULIC 94B	ALEP	$e^+e^- \to Z$

[65] BARATE 98C combines results from $D_s h$-ℓ/Q_{hem}, $D_s h$-K in the same side, $D_s\ell$-ℓ/Q_{hem} and $D_s\ell$-K in the same side.

[66] Uses ℓ-Q_{hem}.

[67] ADAM 97 combines results from $D_s\ell$-Q_{hem}, ℓ-Q_{hem}, and ℓ-ℓ.

[68] Uses ℓ-ℓ.

[69] BUSKULIC 96M uses D_s lepton correlations and lepton, kaon, and jet charge tags.

[70] BUSKULIC 95J uses ℓ-Q_{hem}. They find $\Delta m_s > 5.6$ [> 6.1] for f_s=10% [12%]. We interpolate to our central value f_s=10.5%.

$x_s = \Delta m_{B_s^0}/\Gamma_{B_s^0}$

This is derived from "OUR EVALUATION" of $\Delta m_{B_s^0}$ measurements and $\tau_{B_s^0}$ = 1.54 ps, our central value.

VALUE	CL%	DOCUMENT ID
>14.0 (CL = 95%) OUR EVALUATION		

χ_s

This B_s^0-$\overline{B}_s^0$ integrated mixing parameter is derived from x_s above.

VALUE	CL%	DOCUMENT ID
>0.4975 (CL = 95%) OUR EVALUATION		

B_s^0 REFERENCES

ABE 98 PR D57 R3811 F. Abe+ (CDF Collab.)
ABE 98B PR D57 5382 F. Abe+ (CDF Collab.)
ACKERSTAFF 98F EPJ C2 407 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 98G PL B426 161 K. Ackerstaff+ (OPAL Collab.)
BARATE 98C EPJ C (to be publ.) R. Barate+ (ALEPH Collab.)
CERN-PPE/97-157
ABE 97I PR D55 2546 F. Abe+ (CDF Collab.)
ACCIARRI 97B PL B391 474 M. Acciarri+ (L3 Collab.)
ACCIARRI 97C PL B391 481 M. Acciarri+ (L3 Collab.)
ACKERSTAFF 97U ZPHY C76 401 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 97V ZPHY C76 417 K. Ackerstaff+ (OPAL Collab.)
ADAM 97 PL B414 382 W. Adam+ (DELPHI Collab.)
ABE 96B PR D53 3496 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 96L PRL 76 4675 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96N PRL 77 1945 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96Q PR D54 6596 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABREU 96F ZPHY C71 11 +Adam, Adye, Agasi+ (DELPHI Collab.)
ADAM 96D ZPHY C72 207 W. Adam+ (DELPHI Collab.)
ALEXANDER 96 ZPHY C70 357 +Allison, Altekamp+ (OPAL Collab.)
BUSKULIC 96E ZPHY C69 585 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
BUSKULIC 96M PL B377 205 +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
BUSKULIC 96V PL B384 471 +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
PDG 96 PR D54 1
UENO 96 PL B381 365 +Kanda, Olsen, Kirk+ (AMY Collab.)
ABE 95R PRL 74 4988 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 95Z PRL 75 3068 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ACCIARRI 95H PL B363 127 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ACCIARRI 95I PL B363 137 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
AKERS 95G PL B350 273 +Alexander, Allison, Ametewee+ (OPAL Collab.)
AKERS 95J ZPHY C66 555 +Alexander, Allison, Ametewee+ (OPAL Collab.)
BUSKULIC 95J PL B356 409 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
BUSKULIC 95O PL B361 221 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
ABREU 94D PL B324 500 +Adam, Adye, Agasi, Aleksan+ (DELPHI Collab.)
ABREU 94E ZPHY C61 407 +Adam, Adye, Agasi, Aleksan+ (DELPHI Collab.)
Also 92M PL B289 199 Abreu, Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ABREU 94F PL B322 459 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ABREU 94J PL B332 488 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACCIARRI 94D PL B335 542 +Adam, Adriani, Aguilar-Benitez, Ahlen+ (L3 Collab.)
AKERS 94J PL B337 196 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94L PL B337 393 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
ALBAJAR 94 ZPHY C61 41 +Ankoviak, Bartha, Bezaguet, Boehrer+ (UA1 Collab.)
BUSKULIC 94B PL B322 441 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
BUSKULIC 94C PL B322 275 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
BUSKULIC 94G ZPHY C62 179 +Casper, De Bonis, Decamp, Ghez+ (ALEPH Collab.)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
ABE 93F PRL 71 1685 +Albrow, Amidei, Anway-Wiese+ (CDF Collab.)
ABREU 93C PL B301 145 +Adam, Adye, Agasi, Aleksan+ (DELPHI Collab.)
ACTON 93H PL B312 501 +Akers, Alexander, Allison, Anderson+ (OPAL Collab.)
AKERS 93B ZPHY C60 199 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
BUSKULIC 93G PL B311 425 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
ABREU 92M PL B289 199 +Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ACTON 92C PL B276 379 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ACTON 92N PL B295 357 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADEVA 92C PL B288 395 +Adriani, Aguilar-Benitez, Ahlen+ (L3 Collab.)
BUSKULIC 92B PL B284 177 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
BUSKULIC 92E PL B294 145 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
ABE 91G PRL 67 3351 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ALBAJAR 91D PL B262 171 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
DECAMP 91 PL B258 236 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ADEVA 90P PL B252 703 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB II Collab.)
WEIR 90 PL B240 289 +Abrams, Adolphsen, Alexander, Alvarez+ (Mark II Collab.)
BAND 88 PL B200 221 +Camporesi, Chadwick+ (MAC Collab.)
ALBAJAR 87C PL B186 247 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
SCHAAD 85 PL 160B 188 +Nelson, Abrams, Amidei+ (Mark II Collab.)

B_s^*

$I(J^P) = 0(1^-)$

OMITTED FROM SUMMARY TABLE

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

B_s^* MASS

From mass difference below and the B_s^0 mass.

VALUE (MeV)	DOCUMENT ID
5416.3±3.3 OUR FIT	

$m_{B_s^*} - m_{B_s}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
47.0±2.6 OUR FIT			
47.0±2.6	[1] LEE-FRANZINI 90	CSB2	$e^+e^- \to \Upsilon(5S)$

[1] LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value for B_s.

$|(m_{B_s^*} - m_{B_s}) - (m_{B^*} - m_B)|$

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
<6	95	ABREU 95R	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV

B_s^* DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B_s\gamma$	dominant

B_s^* REFERENCES

ABREU 95R ZPHY C68 353 +Adam, Adye, Agasi+ (DELPHI Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB II Collab.)

$B_{sJ}^*(5850)$

$I(J^P) = ?(?^?)$
I, *J*, *P* need confirmation.

OMITTED FROM SUMMARY TABLE

Signal can be interpreted as coming from $\overline{b}s$ states. Needs confirmation.

$B_{sJ}^*(5850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
5853±15	141	AKERS 95E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

$B_{sJ}^*(5850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
47±22	141	AKERS 95E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

$B_{sJ}^*(5850)$ REFERENCES

AKERS 95E ZPHY C66 19 +Alexander, Allison+ (OPAL Collab.)

BOTTOM, CHARMED MESONS
$(B = C = \pm1)$

$B_c^+ = c\overline{b}$, $B_c^- = \overline{c}b$, similarly for B_c^*'s

$B_c^{\pm}$

$I(J^P) = 0(0^-)$

OMITTED FROM SUMMARY TABLE

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

B_c^+ DECAY MODES

B_c^- modes are charge conjugates of the modes below.

	Mode
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$anything
Γ_2	$J/\psi(1S)\pi^+$
Γ_3	$J/\psi(1S)\pi^+\pi^+\pi^-$

B_c^+ BRANCHING RATIOS

$\Gamma(J/\psi(1S)\ell^+\nu_\ell\text{anything})/\Gamma_{\text{total}} \times B(\overline{b} \to B_c)$ — **$\Gamma_1/\Gamma \times B$**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.2 \times 10^{-4}$	90	[1] BARATE	97H	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.9 \times 10^{-4}$	90	[2] ABREU	97E	DLPH	$e^+e^- \to Z$

[1] BARATE 97H reports $B(Z \to B_c X)/B(Z \to q\overline{q}) \cdot B(B_c \to J/\psi(1S)\ell\nu_\ell) < 5.2 \times 10^{-5}$ at 90%CL. We rescale to our PDG 96 values of $B(Z \to b\overline{b})$. A $B_c^+ \to J/\psi(1S)\mu^+\nu_\mu$ candidate event is found, compared to all the known background sources 2×10^{-3}, which gives $m_{B_c} = 5.96^{+0.25}_{-0.19}$ GeV and $\tau_{B_c} = 1.77 \pm 0.17$ ps.

[2] ABREU 97E value listed is for an assumed $\tau_{B_c} = 0.4$ ps and improves to 1.6×10^{-4} for $\tau_{B_c} = 1.4$ ps.

$\Gamma(J/\psi(1S)\pi^+)/\Gamma_{\text{total}} \times B(\overline{b} \to B_c)$ — **$\Gamma_2/\Gamma \times B$**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8.2 \times 10^{-5}$	90	[3] BARATE	97H	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.4 \times 10^{-4}$	90	[4] ABREU	97E	DLPH	$e^+e^- \to Z$
$<2.0 \times 10^{-5}$	95	[5] ABE	96R	CDF	$p\overline{p}$ 1.8 TeV

[3] BARATE 97H reports $B(Z \to B_c X)/B(Z \to q\overline{q}) \cdot B(B_c \to J/\psi(1S)\pi) < 3.6 \times 10^{-5}$ at 90%CL. We rescale to our PDG 96 values of $B(Z \to b\overline{b})$.

[4] ABREU 97E value listed is for an assumed $\tau_{B_c} = 0.4$ ps and improves to 2.7×10^{-4} for $\tau_{B_c} = 1.4$ ps.

[5] ABE 96R reports $B(b \to B_c X)/B(b \to B^+ X) \cdot B(B_c^+ \to J/\psi(1S)\pi^+)/B(B^+ \to J/\psi(1S)K^+) < 0.053$ at 95%CL for $\tau_{B_c} = 0.8$ ps. It changes from 0.15 to 0.04 for 0.17 ps$< \tau_{B_c} <$ 1.6 ps. We rescale to our PDG 96 values of $B(b \to B^+) = 0.378 \pm 0.022$ and $B(B^+ \to J/\psi(1S)K^+) = 0.00101 \pm 0.00014$.

$\Gamma(J/\psi(1S)\pi^+\pi^+\pi^-)/\Gamma_{\text{total}} \times B(\overline{b} \to B_c)$ — **$\Gamma_3/\Gamma \times B$**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5.7 \times 10^{-4}$	90	[6] ABREU	97E	DLPH	$e^+e^- \to Z$

[6] ABREU 97E value listed is independent of 0.4 ps$< \tau_{B_c} <$ 1.4 ps.

$B_c^{\pm}$ REFERENCES

ABREU	97E	PL B398 207	P. Abreu+	(DELPHI Collab.)
BARATE	97H	PL B402 213	R. Barate+	(ALEPH Collab.)
ABE	96R	PRL 77 5176	+Akimoto, Akopian, Albrow+	(CDF Collab.)
PDG	96	PR D54 1		

$c\overline{c}$ MESONS

$\eta_c(1S)$

$I^G(J^{PC}) = 0^+(0^{-+})$

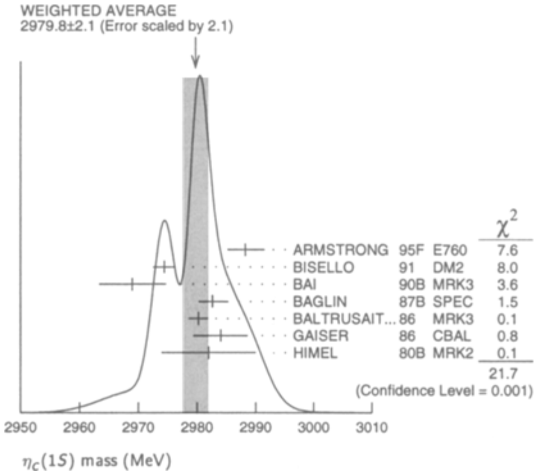
$\eta_c(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2979.8± 2.1 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.		
$2988.3^{+3.3}_{-3.1}$		ARMSTRONG 95F	E760	$\overline{p}p \to \gamma\gamma$
2974.4± 1.9		[1] BISELLO 91	DM2	$J/\psi \to \eta_c\gamma$
2969 ± 4 ± 4	80	BAI 90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
$2982.6^{+2.7}_{-2.3}$	12	BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$
2980.2± 1.6		[1] BALTRUSAIT...86	MRK3	$J/\psi \to \eta_c\gamma$
2984 ± 2.3± 4.0		GAISER 86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
2982 ± 8	18	[2] HIMEL 80B	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2956 ±12 ±12		BAI 90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_SK^0_L$
2976 ± 8		[3] BALTRUSAIT...84	MRK3	$J/\psi \to 2\phi\gamma$
2980 ± 9		[2] PARTRIDGE 80B	CBAL	e^+e^-

[1] Average of several decay modes.

[2] Mass adjusted by us to correspond to $J/\psi(1S)$ mass = 3097 MeV.

[3] $\eta_c \to \phi\phi$.



$\eta_c(1S)$ WIDTH

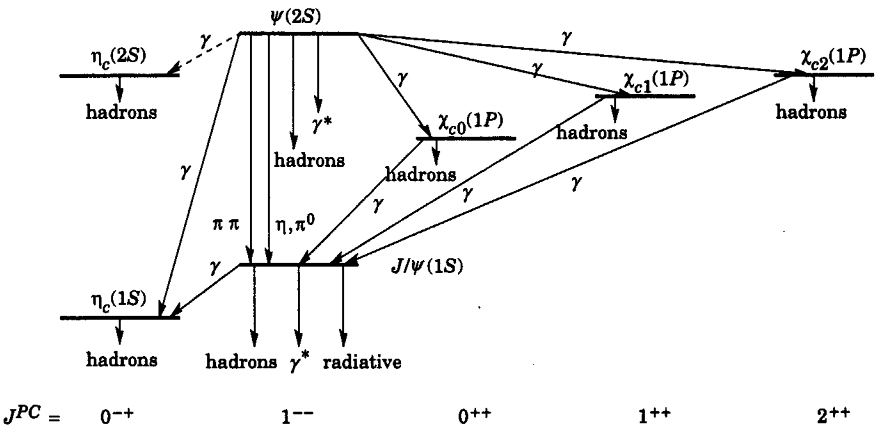
VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$13.2^{+3.8}_{-3.2}$ OUR AVERAGE					
$23.9^{+12.6}_{-7.1}$			ARMSTRONG 95F	E760	$\overline{p}p \to \gamma\gamma$
$7.0^{+7.5}_{-7.0}$		12	BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$
$10.1^{+33.0}_{-8.2}$		23	[4] BALTRUSAIT...86	MRK3	$J/\psi \to \gamma p\overline{p}$
11.5± 4.5			GAISER 86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<40	90	18	HIMEL 80B	MRK2	e^+e^-
<20	90		PARTRIDGE 80B	CBAL	e^+e^-

[4] Positive and negative errors correspond to 90% confidence level.

$\eta_c(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Decays involving hadronic resonances		
Γ_1	$\eta'(958)\pi\pi$	(4.1 ± 1.7) %	
Γ_2	$\rho\rho$	(2.6 ± 0.9) %	
Γ_3	$K^*(892)^0K^-\pi^+$ + c.c.	(2.0 ± 0.7) %	
Γ_4	$K^*(892)\overline{K}^*(892)$	$(8.5 \pm 3.1) \times 10^{-3}$	
Γ_5	$\phi\phi$	$(7.1 \pm 2.8) \times 10^{-3}$	
Γ_6	$a_0(980)\pi$	< 2 %	90%
Γ_7	$a_2(1320)\pi$	< 2 %	90%
Γ_8	$K^*(892)\overline{K}$ + c.c.	< 1.28 %	90%
Γ_9	$f_2(1270)\eta$	< 1.1 %	90%
Γ_{10}	$\omega\omega$	$< 3.1 \times 10^{-3}$	90%
	Decays into stable hadrons		
Γ_{11}	$K\overline{K}\pi$	(5.5 ± 1.7) %	
Γ_{12}	$\eta\pi\pi$	(4.9 ± 1.8) %	
Γ_{13}	$\pi^+\pi^-K^+K^-$	$(2.0 ^{+0.7}_{-0.6})$ %	
Γ_{14}	$2(K^+K^-)$	(2.1 ± 1.2) %	
Γ_{15}	$2(\pi^+\pi^-)$	(1.2 ± 0.4) %	
Γ_{16}	$p\overline{p}$	$(1.2 \pm 0.4) \times 10^{-3}$	
Γ_{17}	$K\overline{K}\eta$	< 3.1 %	90%
Γ_{18}	$\pi^+\pi^-p\overline{p}$	< 1.2 %	90%
Γ_{19}	$\Lambda\overline{\Lambda}$	$< 2 \times 10^{-3}$	90%
	Radiative decays		
Γ_{20}	$\gamma\gamma$	$(3.0 \pm 1.2) \times 10^{-4}$	

THE CHARMONIUM SYSTEM



The current state of knowledge of the charmonium system and transitions, as interpreted by the charmonium model. Uncertain states and transitions are indicated by dashed lines. The notation γ^* refers to decay processes involving intermediate virtual photons, including decays to e^+e^- and $\mu^+\mu^-$.

$\eta_c(1S)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_{20}

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
$7.5^{+1.6}_{-1.4}$ OUR AVERAGE					
$6.7^{+2.4}_{-1.7}\pm2.3$		ARMSTRONG	95F	E760	$\bar{p}p\to\gamma\gamma$
11.3 ± 4.2		ALBRECHT	94H	ARG	$\gamma\gamma$
$8.0\pm2.3\pm2.4$	17	ADRIANI	93N	L3	$e^+e^-\to e^+e^-\eta_c$
$5.9^{+2.1}_{-1.8}\pm1.9$		CHEN	90B	CLEO	$e^+e^-\to e^+e^-\eta_c$
$6.4^{+5.0}_{-3.4}$		AIHARA	88D	TPC	$e^+e^-\to e^+e^-X$
28 ± 15		[5] BERGER	86	PLUT	$\gamma\gamma\to K\bar{K}\pi$

[5] Re-evaluated by AIHARA 88D.

$\eta_c(1S)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\bar{K}\pi)\times\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_{11}\Gamma_{20}/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.94 ± 0.18 OUR AVERAGE						
0.84 ± 0.21			[6] ALBRECHT	94H	ARG	$\gamma\gamma\to K^\pm K^0_S\pi^\mp$
$1.06\pm0.41\pm0.27$		11	BRAUNSCH...	89	TASS	$\gamma\gamma\to K\bar{K}\pi$
$1.5\ {}^{+0.60}_{-0.45}\pm0.3$		7	[6] BERGER	86	PLUT	$\gamma\gamma\to K\bar{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.63	95		[6] BEHREND	89	CELL	$\gamma\gamma\to K^0_S K^\pm\pi^\mp$
<4.4	95		ALTHOFF	85B	TASS	$\gamma\gamma\to K\bar{K}\pi$

[6] $K^\pm K^0_S\pi^\mp$ corrected to $K\bar{K}\pi$ by factor 3.

$\eta_c(1S)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(\eta'(958)\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.041 ± 0.017	14	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(\rho\rho)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
26 ± 9 OUR EVALUATION (Treating systematicerrors as correlated.)						
25 ± 8 OUR AVERAGE						
$26.0\pm2.4\pm8.8$		113	[7] BISELLO	91	DM2	$J/\psi\to\gamma\rho^0\rho^0$
$23.6\pm10.6\pm8.2$		32	[7] BISELLO	91	DM2	$J/\psi\to\gamma\rho^+\rho^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<140	90		[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(K^*(892)^0K^-\pi^+ + \text{c.c.})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.02 ± 0.007	63	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(K^*(892)\bar{K}^*(892))/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85 ± 31 OUR AVERAGE					
$82\pm28\pm27$	14	[7] BISELLO	91	DM2	$e^+e^-\to\gamma K^+K^-\pi^+\pi^-$
90 ± 50	9	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(K^*(892)\bar{K} + \text{c.c.})/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0128	90	BISELLO	91	DM2	$J/\psi\to\gamma K^0_S K^\pm\pi^\mp$
<0.0132	90	[7] BISELLO	91	DM2	$J/\psi\to\gamma K^+K^-\pi^0$

$\Gamma(\phi\phi)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
71 ± 28 OUR EVALUATION (Treating systematic errors as correlated.)					
71 ± 22 OUR AVERAGE					
$74\pm18\pm24$	80	[7] BAI	90B	MRK3	$J/\psi\to\gamma K^+K^-K^+K^-$
$67\pm21\pm24$		[7] BAI	90B	MRK3	$J/\psi\to\gamma K^+K^-K^0_SK^0_L$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$31\pm7\pm10$	19	[7] BISELLO	91	DM2	$J/\psi\to\gamma K^+K^-K^+K^-$
$30^{+18}_{-12}\pm10$	5	[7] BISELLO	91	DM2	$J/\psi\to\gamma K^+K^-K^0_SK^0_L$

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7,8] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(a_2(1320)\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(f_2(1270)\eta)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0031	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0063		[7] BISELLO	91	DM2	$J/\psi\to\gamma\omega\omega$

$\Gamma(K\bar{K}\pi)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.055 ± 0.017 OUR EVALUATION (Treating systematic errors as correlated.)						
0.055 ± 0.008 OUR AVERAGE						
$0.0690\pm0.0142\pm0.0132$		33	[7] BISELLO	91	DM2	$J/\psi\to\gamma K^+K^-\pi^0$
$0.0543\pm0.0094\pm0.0094$		68	[7] BISELLO	91	DM2	$J/\psi\to\gamma K^\pm\pi^\mp K^0_S$
0.048 ± 0.011		95	[7,9] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
$0.161\ {}^{+0.092}_{-0.073}$			[10] HIMEL	80B	MRK2	$\psi(2S)\to\eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.107	90		[7] PARTRIDGE	80B	CBAL	$J/\psi\to\eta_c\gamma$

$\Gamma(\eta\pi\pi)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.049 ± 0.018 OUR EVALUATION					
0.047 ± 0.015 OUR AVERAGE					
0.054 ± 0.020	75	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
$0.037\pm0.013\pm0.020$	18	[7] PARTRIDGE	80B	CBAL	$J/\psi\to\eta\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.020^{+0.007}_{-0.006}$ OUR AVERAGE					
0.021 ± 0.007	110	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
$0.014^{+0.022}_{-0.009}$		[10] HIMEL	80B	MRK2	$\psi(2S)\to\eta_c\gamma$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ± 0.004 OUR EVALUATION					
0.0120 ± 0.0031 OUR AVERAGE					
$0.0105\pm0.0017\pm0.0034$	137	[7] BISELLO	91	DM2	$J/\psi\to\gamma2\pi^+2\pi^-$
0.013 ± 0.006	25	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
$0.020\ {}^{+0.015}_{-0.010}$		[10] HIMEL	80B	MRK2	$\psi(2S)\to\eta_c\gamma$

$\Gamma(2(K^+K^-))/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.021\pm0.010\pm0.006$	ALBRECHT	94H	ARG	$\gamma\gamma\to K^+K^-K^+K^-$

$\Gamma(p\bar{p})/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
12 ± 4 OUR AVERAGE					
$10\pm3\pm4$	18	[7] BISELLO	91	DM2	$J/\psi\to\gamma p\bar{p}$
11 ± 6	23	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$
29^{+29}_{-15}		[10] HIMEL	80B	MRK2	$\psi(2S)\to\eta_c\gamma$

$\Gamma(K\bar{K}\eta)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.031	90	[7] BALTRUSAIT...	86	MRK3	$J/\psi\to\eta_c\gamma$

$\Gamma(\pi^+\pi^-p\bar{p})/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	HIMEL	80B	MRK2	$\psi(2S)\to\eta_c\gamma$

$\Gamma(\Lambda\bar{\Lambda})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	[7] BISELLO	91	DM2	$e^+e^-\to\gamma\Lambda\bar{\Lambda}$

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\bar{p}\to\eta_c(1S)\to\phi\phi$ $\Gamma_{16}\Gamma_5/\Gamma^2$

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
$4.0^{+3.5}_{-3.2}$	BAGLIN	89	SPEC	$\bar{p}p\to K^+K^-K^+K^-$

[7] The quoted branching ratios use $B(J/\psi(1S)\to\gamma\eta_c(1S)) = 0.0127\pm0.0036$. Where relevant, the error in this branching ratio is treated as a common systematic in computing averages.

[8] We are assuming $B(a_0(980)\to\eta\pi) > 0.5$.

[9] Average from $K^+K^-\pi^0$ and $K^\pm K^0$'s$\pi^\mp$ decay channels.

[10] Estimated using $B(\psi(2S)\to\gamma\eta_c(1S)) = 0.0028\pm0.0006$.

RADIATIVE DECAYS

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
3.0 ±1.2 OUR AVERAGE				
$2.80^{+0.67}_{-0.58} \pm 1.0$		ARMSTRONG 95F	E760	$\overline{p}p \to \gamma\gamma$
$6\ ^{+4}_{-3}\ \pm 4$		BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 9	90	[7] BISELLO 91	DM2	$J/\psi \to \gamma\gamma\gamma$
<18	90	[11] BLOOM 83	CBAL	$J/\psi \to \eta_c\gamma$

[11] Using $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$.

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \eta_c(1S) \to \gamma\gamma$ $\Gamma_{16}\Gamma_{20}/\Gamma^2$

VALUE (units 10^{-6})	EVTS	DOCUMENT ID	TECN	COMMENT
$0.36\ ^{+0.08}_{-0.07}$ OUR AVERAGE Error includes scale factor of 1.1.				
$0.336^{+0.080}_{-0.070}$		ARMSTRONG 95F	E760	$\overline{p}p \to \gamma\gamma$
$0.68\ ^{+0.42}_{-0.31}$	12	BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$

$\eta_c(1S)$ REFERENCES

ARMSTRONG 95F PR D52 4839 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ALBRECHT 94H PL B338 390 +Hamacher, Hofmann+ (ARGUS Collab.)
ADRIANI 93N PL B318 575 +Aguilar-Benitez, Ahlen+ (L3 Collab.)
BISELLO 91 NP B350 1 +Busetto+ (DM2 Collab.)
BAI 90B PRL 65 1309 +Blaylock+ (Mark III Collab.)
CHEN 90B PL B243 169 +McIlwain+ (CLEO Collab.)
BAGLIN 89 PL B231 557 +Baird, Bassompierre (R704 Collab.)
BEHREND 89 ZPHY C42 367 +Criegee+ (CELLO Collab.)
BRAUNSCH... 89 ZPHY C41 533 Braunschweig, Bock+ (TASSO Collab.)
AIHARA 88D PRL 60 2355 +Alston-Garnjost+ (TPC Collab.)
BAGLIN 87B PL B187 191 +Baird, Bassompierre, Borreani+ (R704 Collab.)
BALTRUSAIT... 86 PR D33 629 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
BERGER 86 PL 167B 120 +Genzel, Lackas, Pielorz+ (PLUTO Collab.)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BALTRUSAIT... 84 PRL 52 2126 Baltrusaitis+ (CIT, UCSC, ILL, SLAC, WASH) JP
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
HIMEL 80B PRL 45 1146 +Trilling, Abrams, Alam+ (SLAC, LBL, UCB)
PARTRIDGE 80B PRL 45 1150 +Peck+ (CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

ARMSTRONG 89 PL B221 216 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)

$J/\psi(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3096.88±0.04 OUR AVERAGE				
3096.87±0.03±0.03		ARMSTRONG 93B	E760	$\overline{p}p \to e^+e^-$
3096.95±0.1 ±0.3	193	BAGLIN 87	SPEC	$\overline{p}p \to e^+e^-X$
3096.93±0.09	502	ZHOLENTZ 80	REDE	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3097.5 ±0.3		GRIBUSHIN 96	FMPS	$515\ \pi^-\text{Be} \to 2\mu X$
3098.4 ±2.0	38k	LEMOIGNE 82	GOLI	$190\ \pi^-\text{Be} \to 2\mu$
3097.0 ±1		[1] BRANDELIK 79C	DASP	e^+e^-

[1] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$ and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$J/\psi(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
87 ± 5 OUR AVERAGE			
84.4± 8.9	BAI 95B	BES	e^+e^-
99 ±12 ±6	ARMSTRONG 93B	E760	$\overline{p}p \to e^+e^-$
$85.5^{+\ 6.1}_{-\ 5.8}$	[2] HSUEH 92	RVUE	See Υ mini-review

[2] Using data from COFFMAN 92, BALDINI-CELIO 75, BOYARSKI 75, ESPOSITO 75B, BRANDELIK 79C.

$J/\psi(1S)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons		(87.7 ± 0.5) %	
Γ_2	virtual $\gamma \to$ hadrons		(17.0 ± 2.0) %	
Γ_3	e^+e^-		(6.02 ± 0.19) %	
Γ_4	$\mu^+\mu^-$		(6.01 ± 0.19) %	
	Decays involving hadronic resonances			
Γ_5	$\rho\pi$		(1.27 ± 0.09) %	
Γ_6	$\rho^0\pi^0$		$(4.2 \pm 0.5) \times 10^{-3}$	
Γ_7	$a_2(1320)\rho$		(1.09 ± 0.22) %	
Γ_8	$\omega\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$	
Γ_9	$\omega\pi^+\pi^-$		$(7.2 \pm 1.0) \times 10^{-3}$	
Γ_{10}	$\omega f_2(1270)$		$(4.3 \pm 0.6) \times 10^{-3}$	
Γ_{11}	$K^*(892)^0\overline{K}{}^*_2(1430)^0 +$ c.c.		$(6.7 \pm 2.6) \times 10^{-3}$	
Γ_{12}	$\omega K^*(892)\overline{K} +$ c.c.		$(5.3 \pm 2.0) \times 10^{-3}$	
Γ_{13}	$K^+\overline{K}{}^*(892)^- +$ c.c.		$(5.0 \pm 0.4) \times 10^{-3}$	
Γ_{14}	$K^0\overline{K}{}^*(892)^0 +$ c.c.		$(4.2 \pm 0.4) \times 10^{-3}$	
Γ_{15}	$\omega\pi^0\pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$	
Γ_{16}	$b_1(1235)^{\pm}\pi^{\mp}$	[a]	$(3.0 \pm 0.5) \times 10^{-3}$	
Γ_{17}	$\omega K^{\pm}K^0_S\pi^{\mp}$	[a]	$(3.0 \pm 0.7) \times 10^{-3}$	
Γ_{18}	$b_1(1235)^0\pi^0$		$(2.3 \pm 0.6) \times 10^{-3}$	
Γ_{19}	$\phi K^*(892)\overline{K} +$ c.c.		$(2.04 \pm 0.28) \times 10^{-3}$	
Γ_{20}	$\omega K\overline{K}$		$(1.9 \pm 0.4) \times 10^{-3}$	
Γ_{21}	$\omega f_J(1710) \to \omega K\overline{K}$		$(4.8 \pm 1.1) \times 10^{-4}$	
Γ_{22}	$\phi 2(\pi^+\pi^-)$		$(1.60 \pm 0.32) \times 10^{-3}$	
Γ_{23}	$\Delta(1232)^{++}\overline{p}\pi^-$		$(1.6 \pm 0.5) \times 10^{-3}$	
Γ_{24}	$\omega\eta$		$(1.58 \pm 0.16) \times 10^{-3}$	
Γ_{25}	$\phi K\overline{K}$		$(1.48 \pm 0.22) \times 10^{-3}$	
Γ_{26}	$\phi f_J(1710) \to \phi K\overline{K}$		$(3.6 \pm 0.6) \times 10^{-4}$	
Γ_{27}	$p\overline{p}\omega$		$(1.30 \pm 0.25) \times 10^{-3}$	S=1.3
Γ_{28}	$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		$(1.10 \pm 0.29) \times 10^{-3}$	
Γ_{29}	$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[a]	$(1.03 \pm 0.13) \times 10^{-3}$	
Γ_{30}	$p\overline{p}\eta'(958)$		$(9 \pm 4) \times 10^{-4}$	S=1.7
Γ_{31}	$\phi f'_2(1525)$		$(8 \pm 4) \times 10^{-4}$	S=2.7
Γ_{32}	$\phi\pi^+\pi^-$		$(8.0 \pm 1.2) \times 10^{-4}$	
Γ_{33}	$\phi K^{\pm}K^0_S\pi^{\mp}$	[a]	$(7.2 \pm 0.9) \times 10^{-4}$	
Γ_{34}	$\omega f_1(1420)$		$(6.8 \pm 2.4) \times 10^{-4}$	
Γ_{35}	$\phi\eta$		$(6.5 \pm 0.7) \times 10^{-4}$	
Γ_{36}	$\Xi(1530)^-\overline{\Xi}{}^+$		$(5.9 \pm 1.5) \times 10^{-4}$	
Γ_{37}	$pK^-\overline{\Sigma}(1385)^0$		$(5.1 \pm 3.2) \times 10^{-4}$	
Γ_{38}	$\omega\pi^0$		$(4.2 \pm 0.6) \times 10^{-4}$	S=1.4
Γ_{39}	$\phi\eta'(958)$		$(3.3 \pm 0.4) \times 10^{-4}$	
Γ_{40}	$\phi f_0(980)$		$(3.2 \pm 0.9) \times 10^{-4}$	S=1.9
Γ_{41}	$\Xi(1530)^0\overline{\Xi}{}^0$		$(3.2 \pm 1.4) \times 10^{-4}$	
Γ_{42}	$\Sigma(1385)^-\overline{\Sigma}{}^+$ (or c.c.)	[a]	$(3.1 \pm 0.5) \times 10^{-4}$	
Γ_{43}	$\phi f_1(1285)$		$(2.6 \pm 0.5) \times 10^{-4}$	S=1.1
Γ_{44}	$\rho\eta$		$(1.93 \pm 0.23) \times 10^{-4}$	
Γ_{45}	$\omega\eta'(958)$		$(1.67 \pm 0.25) \times 10^{-4}$	
Γ_{46}	$\omega f_0(980)$		$(1.4 \pm 0.5) \times 10^{-4}$	
Γ_{47}	$\rho\eta'(958)$		$(1.05 \pm 0.18) \times 10^{-4}$	
Γ_{48}	$p\overline{p}\phi$		$(4.5 \pm 1.5) \times 10^{-5}$	
Γ_{49}	$a_2(1320)^{\pm}\pi^{\mp}$	[a]	$< 4.3 \times 10^{-3}$	CL=90%
Γ_{50}	$K\overline{K}{}^*_2(1430) +$ c.c.		$< 4.0 \times 10^{-3}$	CL=90%
Γ_{51}	$K^*_2(1430)^0\overline{K}{}^*_2(1430)^0$		$< 2.9 \times 10^{-3}$	CL=90%
Γ_{52}	$K^*(892)^0\overline{K}{}^*(892)^0$		$< 5 \times 10^{-4}$	CL=90%
Γ_{53}	$\phi f_2(1270)$		$< 3.7 \times 10^{-4}$	CL=90%
Γ_{54}	$p\overline{p}\rho$		$< 3.1 \times 10^{-4}$	CL=90%
Γ_{55}	$\phi\eta(1440) \to \phi\eta\pi\pi$		$< 2.5 \times 10^{-4}$	CL=90%
Γ_{56}	$\omega f'_2(1525)$		$< 2.2 \times 10^{-4}$	CL=90%
Γ_{57}	$\Sigma(1385)^0\overline{\Lambda}$		$< 2 \times 10^{-4}$	CL=90%
Γ_{58}	$\Delta(1232)^+\overline{p}$		$< 1 \times 10^{-4}$	CL=90%
Γ_{59}	$\Sigma^0\overline{\Lambda}$		$< 9 \times 10^{-5}$	CL=90%
Γ_{60}	$\phi\pi^0$		$< 6.8 \times 10^{-6}$	CL=90%
	Decays into stable hadrons			
Γ_{61}	$2(\pi^+\pi^-)\pi^0$		(3.37 ± 0.26) %	
Γ_{62}	$3(\pi^+\pi^-)\pi^0$		(2.9 ± 0.6) %	
Γ_{63}	$\pi^+\pi^-\pi^0$		(1.50 ± 0.20) %	
Γ_{64}	$\pi^+\pi^-\pi^0K^+K^-$		(1.20 ± 0.30) %	
Γ_{65}	$4(\pi^+\pi^-)\pi^0$		$(9.0 \pm 3.0) \times 10^{-3}$	
Γ_{66}	$\pi^+\pi^-K^+K^-$		$(7.2 \pm 2.3) \times 10^{-3}$	
Γ_{67}	$K\overline{K}\pi$		$(6.1 \pm 1.0) \times 10^{-3}$	
Γ_{68}	$p\overline{p}\pi^+\pi^-$		$(6.0 \pm 0.5) \times 10^{-3}$	S=1.3
Γ_{69}	$2(\pi^+\pi^-)$		$(4.0 \pm 1.0) \times 10^{-3}$	
Γ_{70}	$3(\pi^+\pi^-)$		$(4.0 \pm 2.0) \times 10^{-3}$	
Γ_{71}	$n\overline{n}\pi^+\pi^-$		$(4 \pm 4) \times 10^{-3}$	
Γ_{72}	$\Sigma^0\overline{\Sigma}{}^0$		$(1.27 \pm 0.17) \times 10^{-3}$	
Γ_{73}	$2(\pi^+\pi^-)K^+K^-$		$(3.1 \pm 1.3) \times 10^{-3}$	
Γ_{74}	$p\overline{p}\pi^+\pi^-\pi^0$	[b]	$(2.3 \pm 0.9) \times 10^{-3}$	S=1.9
Γ_{75}	$p\overline{p}$		$(2.14 \pm 0.10) \times 10^{-3}$	

Γ_{76}	$p\overline{p}\eta$		$(2.09\pm0.18)\times10^{-3}$	
Γ_{77}	$p\overline{n}\pi^-$		$(2.00\pm0.10)\times10^{-3}$	
Γ_{78}	$n\overline{n}$		$(1.9\pm0.5)\times10^{-3}$	
Γ_{79}	$\Xi\overline{\Xi}$		$(1.8\pm0.4)\times10^{-3}$	S=1.8
Γ_{80}	$\Lambda\overline{\Lambda}$		$(1.35\pm0.14)\times10^{-3}$	S=1.2
Γ_{81}	$p\overline{p}\pi^0$		$(1.09\pm0.09)\times10^{-3}$	
Γ_{82}	$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[a]	$(1.06\pm0.12)\times10^{-3}$	
Γ_{83}	$pK^-\overline{\Lambda}$		$(8.9\pm1.6)\times10^{-4}$	
Γ_{84}	$2(K^+K^-)$		$(7.0\pm3.0)\times10^{-4}$	
Γ_{85}	$pK^-\overline{\Sigma}^0$		$(2.9\pm0.8)\times10^{-4}$	
Γ_{86}	K^+K^-		$(2.37\pm0.31)\times10^{-4}$	
Γ_{87}	$\Lambda\overline{\Lambda}\pi^0$		$(2.2\pm0.7)\times10^{-4}$	
Γ_{88}	$\pi^+\pi^-$		$(1.47\pm0.23)\times10^{-4}$	
Γ_{89}	$K^0_SK^0_L$		$(1.08\pm0.14)\times10^{-4}$	
Γ_{90}	$\Lambda\overline{\Sigma}$ + c.c.		$<1.5\times10^{-4}$	CL=90%
Γ_{91}	$K^0_SK^0_S$		$<5.2\times10^{-6}$	CL=90%

Radiative decays

Γ_{92}	$\gamma\eta_c(1S)$		(1.3 ± 0.4) %	
Γ_{93}	$\gamma\pi^+\pi^-2\pi^0$		$(8.3\pm3.1)\times10^{-3}$	
Γ_{94}	$\gamma\eta\pi\pi$		$(6.1\pm1.0)\times10^{-3}$	
Γ_{95}	$\gamma\eta(1440)\rightarrow\gamma K\overline{K}\pi$	[c]	$(9.1\pm1.8)\times10^{-4}$	
Γ_{96}	$\gamma\eta(1440)\rightarrow\gamma\gamma\rho^0$		$(6.4\pm1.4)\times10^{-5}$	
Γ_{97}	$\gamma\eta(1440)\rightarrow\gamma\eta\pi^+\pi^-$		$(3.4\pm0.7)\times10^{-4}$	
Γ_{98}	$\gamma\rho\rho$		$(4.5\pm0.8)\times10^{-3}$	
Γ_{99}	$\gamma\eta'(958)$		$(4.31\pm0.30)\times10^{-3}$	
Γ_{100}	$\gamma2\pi^+2\pi^-$		$(2.8\pm0.5)\times10^{-3}$	S=1.9
Γ_{101}	$\gamma f_4(2050)$		$(2.7\pm0.7)\times10^{-3}$	
Γ_{102}	$\gamma\omega\omega$		$(1.59\pm0.33)\times10^{-3}$	
Γ_{103}	$\gamma\eta(1440)\rightarrow\gamma\rho^0\rho^0$		$(1.7\pm0.4)\times10^{-3}$	S=1.3
Γ_{104}	$\gamma f_2(1270)$		$(1.38\pm0.14)\times10^{-3}$	
Γ_{105}	$\gamma f_J(1710)\rightarrow\gamma K\overline{K}$		$(8.5^{+1.2}_{-0.9})\times10^{-4}$	S=1.2
Γ_{106}	$\gamma\eta$		$(8.6\pm0.8)\times10^{-4}$	
Γ_{107}	$\gamma f_1(1420)\rightarrow\gamma K\overline{K}\pi$		$(8.3\pm1.5)\times10^{-4}$	
Γ_{108}	$\gamma f_1(1285)$		$(6.5\pm1.0)\times10^{-4}$	
Γ_{109}	$\gamma f'_2(1525)$		$(4.7^{+0.7}_{-0.5})\times10^{-4}$	
Γ_{110}	$\gamma\phi\phi$		$(4.0\pm1.2)\times10^{-4}$	S=2.1
Γ_{111}	$\gamma p\overline{p}$		$(3.8\pm1.0)\times10^{-4}$	
Γ_{112}	$\gamma\eta(2225)$		$(2.9\pm0.6)\times10^{-4}$	
Γ_{113}	$\gamma\eta(1760)\rightarrow\gamma\rho^0\rho^0$		$(1.3\pm0.9)\times10^{-4}$	
Γ_{114}	$\gamma\pi^0$		$(3.9\pm1.3)\times10^{-5}$	
Γ_{115}	$\gamma p\overline{p}\pi^+\pi^-$		$<7.9\times10^{-4}$	CL=90%
Γ_{116}	$\gamma\gamma$		$<5\times10^{-4}$	CL=90%
Γ_{117}	$\gamma\Lambda\overline{\Lambda}$		$<1.3\times10^{-4}$	CL=90%
Γ_{118}	3γ		$<5.5\times10^{-5}$	CL=90%
Γ_{119}	$\gamma f_0(2200)$			
Γ_{120}	$\gamma f_J(2220)$		$>2.50\times10^{-3}$	CL=99.9%
Γ_{121}	$\gamma f_0(1500)$		$(5.7\pm0.8)\times10^{-4}$	
Γ_{122}	γe^+e^-		$(8.8\pm1.4)\times10^{-3}$	

[a] The value is for the sum of the charge states of particle/antiparticle states indicated.

[b] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[c] See the "Note on the $\eta(1440)$" in the $\eta(1440)$ Particle Listings.

$J/\psi(1S)$ PARTIAL WIDTHS

Γ(hadrons) Γ_1

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
74.1 ± 8.1	BAI 95B	BES	e^+e^-
59 ± 24	BALDINI-... 75	FRAG	e^+e^-
59 ± 14	BOYARSKI 75	MRK1	e^+e^-
50 ± 25	ESPOSITO 75B	FRAM	e^+e^-

$\Gamma(\text{virtual}\,\gamma\rightarrow\text{hadrons})$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
12 ±2	[3] BOYARSKI 75	MRK1	e^+e^-

[3] Included in Γ(hadrons).

$\Gamma(e^+e^-)$ Γ_3

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
5.26±0.37 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.14 ± 0.39	BAI 95B	BES	e^+e^-
$5.36^{+0.29}_{-0.28}$	[4] HSUEH 92	RVUE	See Υ mini-review
4.72 ± 0.35	ALEXANDER 89	RVUE	See Υ mini-review
4.4 ± 0.6	[4] BRANDELIK 79C	DASP	e^+e^-
4.6 ± 0.8	[5] BALDINI-... 75	FRAG	e^+e^-
4.8 ± 0.6	BOYARSKI 75	MRK1	e^+e^-
4.6 ± 1.0	ESPOSITO 75B	FRAM	e^+e^-

[4] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

[5] Assuming equal partial widths for e^+e^- and $\mu^+\mu^-$.

$\Gamma(\mu^+\mu^-)$ Γ_4

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.13 ± 0.52	BAI 95B	BES	e^+e^-
4.8 ± 0.6	BOYARSKI 75	MRK1	e^+e^-
5 ± 1	ESPOSITO 75B	FRAM	e^+e^-

$\Gamma(\gamma\gamma)$ Γ_{116}

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<5.4	90	BRANDELIK 79C	DASP	e^+e^-

$J/\psi(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel_i in the e^+e^- annihilation.

$\Gamma(\text{hadrons})\times\Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4 ± 0.8	[6] BALDINI-... 75	FRAG	e^+e^-
3.9 ± 0.8	[6] ESPOSITO 75B	FRAM	e^+e^-

$\Gamma(e^+e^-)\times\Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_3\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.35 ± 0.02	BRANDELIK 79C	DASP	e^+e^-
0.32 ± 0.07	[6] BALDINI-... 75	FRAG	e^+e^-
0.34 ± 0.09	[6] ESPOSITO 75B	FRAM	e^+e^-
0.36 ± 0.10	[6] FORD 75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-)\times\Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.51 ± 0.09	DASP 75	DASP	e^+e^-
0.38 ± 0.05	[6] ESPOSITO 75B	FRAM	e^+e^-

$\Gamma(p\overline{p})\times\Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_{75}\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
9.7±1.7	[7] ARMSTRONG 93B	E760	$\overline{p}p\rightarrow e^+e^-$

[6] Data redundant with branching ratios or partial widths above.

[7] Using $\Gamma_{\text{total}} = 85.5^{+6.1}_{-5.8}$ MeV.

$J/\psi(1S)$ BRANCHING RATIOS

For the first four branching ratios, see also the partial widths, and (partial widths) × $\Gamma(e^+e^-)/\Gamma_{\text{total}}$ above.

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.877±0.005 OUR AVERAGE			
0.878 ± 0.005	BAI 95B	BES	e^+e^-
0.86 ± 0.02	BOYARSKI 75	MRK1	e^+e^-

$\Gamma(\text{virtual}\,\gamma\rightarrow\text{hadrons})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.17 ±0.02	[8] BOYARSKI 75	MRK1	e^+e^-

[8] Included in $\Gamma(\text{hadrons})/\Gamma_{\text{total}}$.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0602±0.0019 OUR AVERAGE			
0.0609 ± 0.0033	BAI 95B	BES	e^+e^-
$0.0592\pm0.0015\pm0.0020$	COFFMAN 92	MRK3	$\psi(2S)\rightarrow J/\psi\pi^+\pi^-$
0.069 ± 0.009	BOYARSKI 75	MRK1	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0601±0.0019 OUR AVERAGE				
0.0608±0.0033	BAI	95B	BES	e^+e^-
0.0590±0.0015±0.0019	COFFMAN	92	MRK3	$\psi(2S) \to J/\psi\pi^+\pi^-$
0.069 ±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00±0.07	BAI	95B	BES	e^+e^-
1.00±0.05	BOYARSKI	75	MRK1	e^+e^-
0.91±0.15	ESPOSITO	75B	FRAM	e^+e^-
0.93±0.10	FORD	75	SPEC	e^+e^-

HADRONIC DECAYS

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0127±0.0009 OUR AVERAGE					
0.0121±0.0020		BAI	96D	BES	$e^+e^- \to \rho\pi$
0.0142±0.0001±0.0019		COFFMAN	88	MRK3	e^+e^-
0.013 ±0.003	150	FRANKLIN	83	MRK2	e^+e^-
0.016 ±0.004	183	ALEXANDER	78	PLUT	e^+e^-
0.0133±0.0021		BRANDELIK	78B	DASP	e^+e^-
0.010 ±0.002	543	BARTEL	76	CNTR	e^+e^-
0.013 ±0.003	153	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\rho^0\pi^0)/\Gamma(\rho\pi)$ Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
0.328±0.005±0.027	COFFMAN	88	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.35 ±0.08	ALEXANDER	78	PLUT	e^+e^-
0.32 ±0.08	BRANDELIK	78B	DASP	e^+e^-
0.39 ±0.11	BARTEL	76	CNTR	e^+e^-
0.37 ±0.09	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(a_2(1320)\rho)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
10.9±2.2 OUR AVERAGE					
11.7±0.7±2.5	7584	AUGUSTIN	89	DM2	$J/\psi \to \rho^0\rho^\pm\pi^\mp$
8.4±4.5	36	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85±34	140	VANNUCCI	77	MRK1	$e^+e^- \to 3(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±1.0 OUR AVERAGE					
7.0±1.6	18058	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
7.8±1.6	215	BURMESTER	77D	PLUT	e^+e^-
6.8±1.9	348	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-)\pi^0)$ Γ_9/Γ_{61}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.3	[9] JEAN-MARIE	76	MRK1	e^+e^-

[9] Final state $(\pi^+\pi^-)\pi^0$ under the assumption that $\pi\pi$ is isospin 0.

$\Gamma(K^*(892)^0\overline{K}{}^*_2(1430)^0 + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
67±26	40	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(\omega K^*(892)\overline{K} + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
53±14±14	530± 140	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_2(1270))/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.3±0.6 OUR AVERAGE					
4.3±0.2±0.6	5860	AUGUSTIN	89	DM2	e^+e^-
4.0±1.6	70	BURMESTER	77D	PLUT	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.9±0.8	81	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(K^+\overline{K}{}^*(892)^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.0 ±0.4 OUR AVERAGE					
4.57±0.17±0.70	2285	JOUSSET	90	DM2	$J/\psi \to$ hadrons
5.26±0.13±0.53		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$, $K^+K^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.6 ±0.6	24	FRANKLIN	83	MRK2	$J/\psi \to K^+K^-\pi^0$
3.2 ±0.6	48	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$
4.1 ±1.2	39	BRAUNSCH...	76	DASP	$J/\psi \to K^\pm X$

$\Gamma(K^0\overline{K}{}^*(892)^0 + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.2 ±0.4 OUR AVERAGE					
3.96±0.15±0.60	1192	JOUSSET	90	DM2	$J/\psi \to$ hadrons
4.33±0.12±0.45		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.7 ±0.6	45	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$

$\Gamma(K^0\overline{K}{}^*(892)^0 + \text{c.c.})/\Gamma(K^+\overline{K}{}^*(892)^- + \text{c.c.})$ Γ_{14}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.82±0.05±0.09	COFFMAN	88	MRK3	$J/\psi \to K\overline{K}{}^*(892)$+c.c.

$\Gamma(\omega\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.4±0.3±0.7	509	AUGUSTIN	89	DM2	$J/\psi \to \pi^+\pi^-3\pi^0$

$\Gamma(b_1(1235)^\pm\pi^\mp)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
30±5 OUR AVERAGE					
31±6	4600	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
29±7	87	BURMESTER	77D	PLUT	e^+e^-

$\Gamma(\omega K^\pm K^0_S\pi^\mp)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
29.5±1.4±7.0	879± 41	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(b_1(1235)^0\pi^0)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
23±3±5	229	AUGUSTIN	89	DM2	e^+e^-

$\Gamma(\phi K^*(892)\overline{K} + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
20.4±2.8 OUR AVERAGE					
20.7±2.4±3.0		FALVARD	88	DM2	$J/\psi \to$ hadrons
20 ±3 ±3	155± 20	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega K\overline{K})/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
19 ± 4 OUR AVERAGE					
19.8± 2.1±3.9		[10] FALVARD	88	DM2	$J/\psi \to$ hadrons
16 ±10	22	FELDMAN	77	MRK1	e^+e^-

[10] Addition of ωK^+K^- and $\omega K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\omega f_J(1710) \to \omega K\overline{K})/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.8±1.1±0.3	[11,12] FALVARD	88	DM2	$J/\psi \to$ hadrons

[11] Includes unknown branching fraction $f_J(1710) \to K\overline{K}$.

[12] Addition of $f_J(1710) \to K^+K^-$ and $f_J(1710) \to K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\phi 2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
16.0±1.0±3.0	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(\Delta(1232)^{++}\overline{p}\pi^-)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.23±0.40	332	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\eta)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.16 OUR AVERAGE					
1.43±0.10±0.21	378	JOUSSET	90	DM2	$J/\psi \to$ hadrons
1.71±0.08±0.20		COFFMAN	88	MRK3	$e^+e^- \to \cdot 3\pi\eta$

$\Gamma(\phi K\overline{K})/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
14.8±2.2 OUR AVERAGE					
14.6±0.8±2.1		[13] FALVARD	88	DM2	$J/\psi \to$ hadrons
18 ±8	14	FELDMAN	77	MRK1	e^+e^-

[13] Addition of ϕK^+K^- and $\phi K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\phi f_J(1710) \to \phi K\overline{K})/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
3.6±0.2±0.6	[14,15] FALVARD	88	DM2	$J/\psi \to$ hadrons

[14] Including interference with $f_2'(1525)$.

[15] Includes unknown branching fraction $f_J(1710) \to K\overline{K}$.

$\Gamma(p\overline{p}\omega)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.30±0.25 OUR AVERAGE Error includes scale factor of 1.3.					
1.10±0.17±0.18	486	EATON	84	MRK2	e^+e^-
1.6 ±0.3	77	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Delta(1232)^{++}\overline{\Delta}(1232)^{--})/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.10±0.09±0.28	233	EATON	84	MRK2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}(1385)^+ \text{(or c.c.)})/\Gamma_{\text{total}}$ Γ_{29}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.03±0.13 OUR AVERAGE					
1.00±0.04±0.21	631 ± 25	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
1.19±0.04±0.25	754 ± 27	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.86±0.18±0.22	56	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
1.03±0.24±0.25	68	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(p\overline{p}\eta'(958))/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.9 ±0.4 OUR AVERAGE Error includes scale factor of 1.7.					
0.68±0.23±0.17	19	EATON	84	MRK2	e^+e^-
1.8 ±0.6	19	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\phi f_2'(1525))/\Gamma_{\text{total}}$ Γ_{31}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
8 ±4 OUR AVERAGE Error includes scale factor of 2.7.					
12.3±0.6±2.0		[16,17] FALVARD	88	DM2	$J/\psi \to$ hadrons
4.8±1.8	46	[16] GIDAL	81	MRK2	$J/\psi \to K^+K^-K^+K^-$

[16] Re-evaluated using $B(f_2'(1525) \to K\overline{K}) = 0.713$.

[17] Including interference with $f_J(1710)$.

$\Gamma(\phi\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.80±0.12 OUR AVERAGE					
0.78±0.03±0.12		FALVARD	88	DM2	$J/\psi \to$ hadrons
2.1 ±0.9	23	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\phi K^\pm K^0_S \pi^\mp)/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
7.2±0.9 OUR AVERAGE					
7.4±0.9±1.1		FALVARD	88	DM2	$J/\psi \to$ hadrons
7 ±0.6±1.0	163 ± 15	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_1(1420))/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$6.8^{+1.9}_{-1.6}\pm1.7$	111^{+31}_{-26}	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\phi\eta)/\Gamma_{\text{total}}$ Γ_{35}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.65 ±0.07 OUR AVERAGE					
0.64 ±0.04 ±0.11	346	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.661±0.045±0.078		COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta$

$\Gamma(\Xi(1530)^-\overline{\Xi}^+)/\Gamma_{\text{total}}$ Γ_{36}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.59±0.09±0.12	75 ± 11	HENRARD	87	DM2	e^+e^-

$\Gamma(pK^-\overline{\Sigma}(1385)^0)/\Gamma_{\text{total}}$ Γ_{37}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.51±0.26±0.18	89	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\pi^0)/\Gamma_{\text{total}}$ Γ_{38}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.42 ±0.06 OUR AVERAGE Error includes scale factor of 1.4.					
0.360±0.028±0.054	222	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.482±0.019±0.064		COFFMAN	88	MRK3	$e^+e^- \to \pi^0\pi^+\pi^-\pi^0$

$\Gamma(\phi\eta'(958))/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.33 ±0.04 OUR AVERAGE						
0.41 ±0.03 ±0.08		167	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.308±0.034±0.036			COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		VANNUCCI	77	MRK1	e^+e^-

$\Gamma(\phi f_0(980))/\Gamma_{\text{total}}$ Γ_{40}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.2±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
4.6±0.4±0.8		[18] FALVARD	88	DM2	$J/\psi \to$ hadrons
2.6±0.6	50	[18] GIDAL	81	MRK2	$J/\psi \to K^+K^-K^+K^-$

[18] Assuming $B(f_0(980) \to \pi\pi) = 0.78$.

$\Gamma(\Xi(1530)^0\overline{\Xi}^0)/\Gamma_{\text{total}}$ Γ_{41}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.32±0.12±0.07	24 ± 9	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}^+ \text{(or c.c.)})/\Gamma_{\text{total}}$ Γ_{42}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.31±0.05 OUR AVERAGE					
0.30±0.03±0.07	74 ± 8	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
0.34±0.04±0.07	77 ± 9	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.29±0.11±0.10	26	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
0.31±0.11±0.11	28	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(\phi f_1(1285))/\Gamma_{\text{total}}$ Γ_{43}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.6±0.5 OUR AVERAGE Error includes scale factor of 1.1.					
3.2±0.6±0.4		JOUSSET	90	DM2	$J/\psi \to \phi 2(\pi^+\pi^-)$
2.1±0.5±0.4	25	[19] JOUSSET	90	DM2	$J/\psi \to \phi\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6±0.2±0.1	16 ± 6	BECKER	87	MRK3	$J/\psi \to \phi K\overline{K}\pi$

[19] We attrribute to the $f_1(1285)$ the signal observed in the $\pi^+\pi^-\eta$ invariant mass distribution at 1297 Mev.

$\Gamma(\rho\eta)/\Gamma_{\text{total}}$ Γ_{44}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.193±0.023 OUR AVERAGE					
0.194±0.017±0.029	299	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.193±0.013±0.029		COFFMAN	88	MRK3	$e^+e^- \to \pi^+\pi^-\eta$

$\Gamma(\omega\eta'(958))/\Gamma_{\text{total}}$ Γ_{45}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.167±0.025 OUR AVERAGE					
$0.18\ ^{+0.10}_{-0.08}\ \pm0.03$	6	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.166±0.017±0.019		COFFMAN	88	MRK3	$e^+e^- \to 3\pi\eta'$

$\Gamma(\omega f_0(980))/\Gamma_{\text{total}}$ Γ_{46}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
1.41±0.27±0.47	[20] AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$

[20] Assuming $B(f_0(980) \to \pi\pi) = 0.78$.

$\Gamma(\rho\eta'(958))/\Gamma_{\text{total}}$ Γ_{47}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.105±0.018 OUR AVERAGE					
0.083±0.030±0.012	19	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.114±0.014±0.016		COFFMAN	88	MRK3	$J/\psi \to \pi^+\pi^-\eta'$

$\Gamma(p\overline{p}\phi)/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
0.45±0.13±0.07	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(a_2(1320)^\pm\pi^\mp)/\Gamma_{\text{total}}$ Γ_{49}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<43	90	BRAUNSCH...	76	DASP	e^+e^-

$\Gamma(K\overline{K}^*_2(1430) + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{50}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<40	90	VANNUCCI	77	MRK1	$e^+e^- \to K^0\overline{K}^{*0}_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<66	90	BRAUNSCH...	76	DASP	$e^+e^- \to K^\pm\overline{K}^{*\mp}_2$

$\Gamma(K_2^*(1430)^0\overline{K}_2^*(1430)^0)/\Gamma_{\text{total}}$ — Γ_{51}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<29	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(K^*(892)^0\overline{K}^*(892)^0)/\Gamma_{\text{total}}$ — Γ_{52}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(\phi f_2(1270))/\Gamma_{\text{total}}$ — Γ_{53}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.7	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.5	90	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(p\overline{p}\rho)/\Gamma_{\text{total}}$ — Γ_{54}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.31	90	EATON	84	MRK2	$e^+e^- \to$ hadronsγ

$\Gamma(\phi\eta(1440) \to \phi\eta\pi\pi)/\Gamma_{\text{total}}$ — Γ_{55}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	[21] FALVARD	88	DM2	$J/\psi \to$ hadrons

[21] Includes unknown branching fraction $\eta(1440) \to \eta\pi\pi$.

$\Gamma(\omega f_2'(1525))/\Gamma_{\text{total}}$ — Γ_{56}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	[22] VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-\pi^0K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	[22] FALVARD	88	DM2	$J/\psi \to$ hadrons

[22] Re-evaluated assuming $B(f_2'(1525) \to K\overline{K}) = 0.713$.

$\Gamma(\Sigma(1385)^0\overline{\Lambda})/\Gamma_{\text{total}}$ — Γ_{57}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Delta(1232)^+\overline{p})/\Gamma_{\text{total}}$ — Γ_{58}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma^0\overline{\Lambda})/\Gamma_{\text{total}}$ — Γ_{59}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.9	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\phi\pi^0)/\Gamma_{\text{total}}$ — Γ_{60}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.068	90	COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\pi^0$

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{61}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0337±0.0026 OUR AVERAGE					
0.0325±0.0049	46055	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
0.0317±0.0042	147	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.0364±0.0052	1500	BURMESTER	77D	PLUT	e^+e^-
0.04 ±0.01	675	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{62}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.029±0.006 OUR AVERAGE					
0.028±0.009	11	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.029±0.007	181	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.015 ±0.002	168	FRANKLIN	83	MRK2	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0K^+K^-)/\Gamma_{\text{total}}$ — Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ±0.003	309	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(4(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{65}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
90±30	13	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ — Γ_{66}/Γ

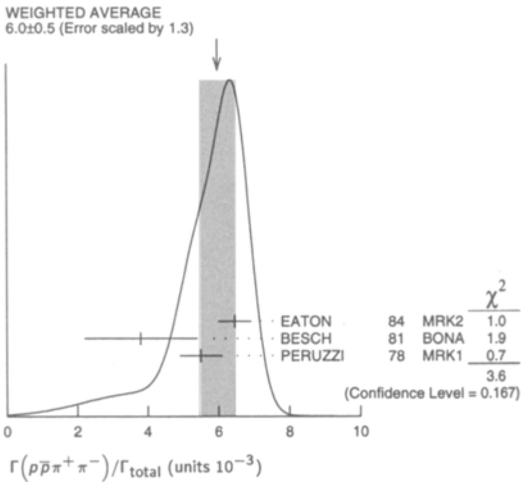
VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
72±23	205	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K\overline{K}\pi)/\Gamma_{\text{total}}$ — Γ_{67}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
61 ±10 OUR AVERAGE					
55.2±12.0	25	FRANKLIN	83	MRK2	$e^+e^- \to K^+K^-\pi^0$
78.0±21.0	126	VANNUCCI	77	MRK1	$e^+e^- \to K_S^0K^\pm\pi^\mp$

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{68}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
6.0 ±0.5 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
6.46±0.17±0.43	1435	EATON	84	MRK2	e^+e^-
3.8 ±1.6	48	BESCH	81	BONA	e^+e^-
5.5 ±0.6	533	PERUZZI	78	MRK1	e^+e^-



$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{69}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.004 ±0.001	76	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{70}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
40±20	32	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(n\overline{n}\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{71}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.8±3.6	5	BESCH	81	BONA	e^+e^-

$\Gamma(\Sigma^0\overline{\Sigma}^0)/\Gamma_{\text{total}}$ — Γ_{72}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.27±0.17 OUR AVERAGE					
1.06±0.04±0.23	884±30	PALLIN	87	DM2	$e^+e^- \to \Sigma^0\overline{\Sigma}^0$
1.58±0.16±0.25	90	EATON	84	MRK2	$e^+e^- \to \Sigma^0\overline{\Sigma}^0$
1.3 ±0.4	52	PERUZZI	78	MRK1	$e^+e^- \to \Sigma^0\overline{\Sigma}^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.4 ±2.6	3	BESCH	81	BONA	$e^+e^- \to \Sigma^+\overline{\Sigma}^-$

$\Gamma(2(\pi^+\pi^-)K^+K^-)/\Gamma_{\text{total}}$ — Γ_{73}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
31±13	30	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(p\overline{p}\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{74}/Γ

Including $p\overline{p}\pi^+\pi^-\gamma$ and excluding ω, η, η'

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.3 ±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
3.36±0.65±0.28	364	EATON	84	MRK2	e^+e^-
1.6 ±0.6	39	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{75}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.14±0.10 OUR AVERAGE					
2.0 ±0.3	48	ANTONELLI	93	SPEC	e^+e^-
1.91±0.04±0.30		PALLIN	87	DM2	e^+e^-
2.16±0.07±0.15	1420	EATON	84	MRK2	e^+e^-
2.5 ±0.4	133	BRANDELIK	79C	DASP	e^+e^-
2.0 ±0.5		BESCH	78	BONA	e^+e^-
2.2 ±0.2	331	[23] PERUZZI	78	MRK1	e^+e^-

[23] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\bar{p}\eta)/\Gamma_{\text{total}}$ Γ_{76}/Γ

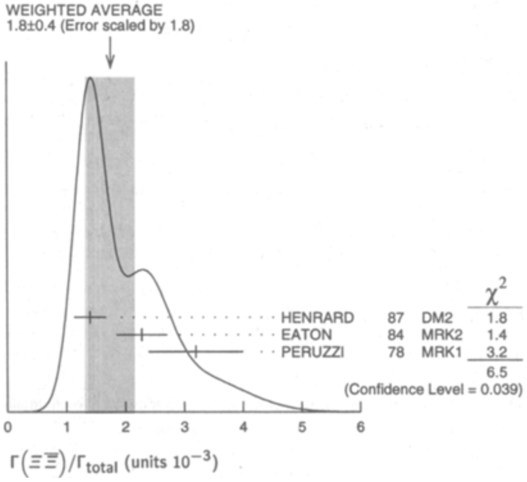
VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.09±0.18 OUR AVERAGE					
2.03±0.13±0.15	826	EATON	84	MRK2	e^+e^-
2.5 ±1.2		BRANDELIK	79C	DASP	e^+e^-
2.3 ±0.4	197	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\bar{n}\pi^-)/\Gamma_{\text{total}}$ Γ_{77}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.00±0.10 OUR AVERAGE					
2.02±0.07±0.16	1288	EATON	84	MRK2	$e^+e^- \to p\pi^-$
1.93±0.07±0.16	1191	EATON	84	MRK2	$e^+e^- \to \bar{p}\pi^+$
1.7 ±0.7	32	BESCH	81	BONA	$e^+e^- \to p\pi^-$
1.6 ±1.2	5	BESCH	81	BONA	$e^+e^- \to \bar{p}\pi^+$
2.16±0.29	194	PERUZZI	78	MRK1	$e^+e^- \to p\pi^-$
2.04±0.27	204	PERUZZI	78	MRK1	$e^+e^- \to \bar{p}\pi^+$

$\Gamma(\Xi\bar{\Xi})/\Gamma_{\text{total}}$ Γ_{79}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.8 ±0.4 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
1.40±0.12±0.24	132±11	HENRARD	87	DM2	$e^+e^- \to \Xi^-\bar{\Xi}^+$
2.28±0.16±0.40	194	EATON	84	MRK2	$e^+e^- \to \Xi^-\bar{\Xi}^+$
3.2 ±0.8	71	PERUZZI	78	MRK1	e^+e^-



$\Gamma(n\bar{n})/\Gamma_{\text{total}}$ Γ_{78}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.19 ±0.05 OUR AVERAGE					
0.190±0.055	40	ANTONELLI	93	SPEC	e^+e^-
0.18 ±0.09		BESCH	78	BONA	e^+e^-

$\Gamma(\Lambda\bar{\Lambda})/\Gamma_{\text{total}}$ Γ_{80}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.35±0.14 OUR AVERAGE	Error includes scale factor of 1.2.				
1.38±0.05±0.20	1847	PALLIN	87	DM2	e^+e^-
1.58±0.08±0.19	365	EATON	84	MRK2	e^+e^-
2.6 ±1.6	5	BESCH	81	BONA	e^+e^-
1.1 ±0.2	196	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\bar{p}\pi^0)/\Gamma_{\text{total}}$ Γ_{81}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.09±0.09 OUR AVERAGE					
1.13±0.09±0.09	685	EATON	84	MRK2	e^+e^-
1.4 ±0.4		BRANDELIK	79C	DASP	e^+e^-
1.00±0.15	109	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Lambda\bar{\Sigma}^-\pi^+ \text{ (or c.c.)})/\Gamma_{\text{total}}$ Γ_{82}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.12 OUR AVERAGE					
0.90±0.06±0.16	225±15	HENRARD	87	DM2	$e^+e^- \to \Lambda\bar{\Sigma}^+\pi^-$
1.11±0.06±0.20	342±18	HENRARD	87	DM2	$e^+e^- \to \Lambda\bar{\Sigma}^-\pi^+$
1.53±0.17±0.38	135	EATON	84	MRK2	$e^+e^- \to \Lambda\bar{\Sigma}^+\pi^-$
1.38±0.21±0.35	118	EATON	84	MRK2	$e^+e^- \to \Lambda\bar{\Sigma}^-\pi^+$

$\Gamma(pK^-\bar{\Lambda})/\Gamma_{\text{total}}$ Γ_{83}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.89±0.07±0.14	307	EATON	84	MRK2	e^+e^-

$\Gamma(2(K^+K^-))/\Gamma_{\text{total}}$ Γ_{84}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7 ±3	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(pK^-\bar{\Sigma}^0)/\Gamma_{\text{total}}$ Γ_{85}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.29±0.06±0.05	90	EATON	84	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_{86}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.37±0.31 OUR AVERAGE					
2.39±0.24±0.22	107	BALTRUSAIT..85D		MRK3	e^+e^-
2.2 ±0.9	6	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\Lambda\bar{\Lambda}\pi^0)/\Gamma_{\text{total}}$ Γ_{87}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.22±0.05±0.05	19±4	HENRARD	87	DM2	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{88}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.47±0.23 OUR AVERAGE					
1.58±0.20±0.15	84	BALTRUSAIT..85D		MRK3	e^+e^-
1.0 ±0.5	5	BRANDELIK	78B	DASP	e^+e^-
1.6 ±1.6	1	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K^0_SK^0_L)/\Gamma_{\text{total}}$ Γ_{89}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.08±0.14 OUR AVERAGE					
1.18±0.12±0.18		JOUSSET	90	DM2	$J/\psi \to$ hadrons
1.01±0.16±0.09	74	BALTRUSAIT..85D		MRK3	e^+e^-

$\Gamma(\Lambda\bar{\Sigma} + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{90}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.15	90	PERUZZI	78	MRK1	$e^+e^- \to \Lambda X$

$\Gamma(K^0_SK^0_S)/\Gamma_{\text{total}}$ Γ_{91}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.052	90	[24] BALTRUSAIT..85C		MRK3	e^+e^-

[24] Forbidden by *CP*.

RADIATIVE DECAYS

$\Gamma(\gamma\eta_c(1S))/\Gamma_{\text{total}}$ Γ_{92}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0127±0.0036		GAISER	86	CBAL	$J/\psi \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	16	BALTRUSAIT..84		MRK3	$J/\psi \to 2\phi\gamma$

$\Gamma(\gamma\pi^+\pi^-2\pi^0)/\Gamma_{\text{total}}$ Γ_{93}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
8.3±0.2±3.1	[25] BALTRUSAIT..86B		MRK3	$J/\psi \to 4\pi\gamma$

[25] 4π mass less than 2.0 GeV.

$\Gamma(\gamma\eta\pi\pi)/\Gamma_{\text{total}}$ Γ_{94}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
6.1 ±1.0 OUR AVERAGE				
5.85±0.3±1.05	[26] EDWARDS	83B	CBAL	$J/\psi \to \eta\pi^+\pi^-$
7.8 ±1.2±2.4	[26] EDWARDS	83B	CBAL	$J/\psi \to \eta 2\pi^0$

[26] Broad enhancement at 1700 MeV.

$\Gamma(\gamma\eta(1440) \to \gamma K\bar{K}\pi)/\Gamma_{\text{total}}$ Γ_{95}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.91±0.18 OUR AVERAGE				
0.83±0.13±0.18	[27,28] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\bar{K}\pi$
$1.03^{+0.21+0.26}_{-0.18-0.19}$	[27,29] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.78±0.21±0.33	[27,30] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\bar{K}\pi$
3.8 ±0.3 ±0.6	[27] AUGUSTIN	90	DM2	$J/\psi \to \gamma K\bar{K}\pi$
$0.66^{+0.17+0.24}_{-0.16-0.15}$	[27,31] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
4.0 ±0.7 ±1.0	[27] EDWARDS	82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$
4.3 ±1.7	[27,32] SCHARRE	80	MRK2	e^+e^-

[27] Includes unknown branching fraction $\eta(1440) \to K\bar{K}\pi$.
[28] From fit to the $K^*(892)K$ 0^{-+} partial wave.
[29] From $K^*(890)K$ final state.
[30] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[31] From $a_0(980)\pi$ final state.
[32] Corrected for spin-zero hypothesis for $\eta(1440)$.

$\Gamma(\gamma\eta(1440) \to \gamma\gamma\rho^0)/\Gamma_{total}$ — Γ_{96}/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
6.4±1.2±0.7	[33] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[33] Includes unknown branching fraction $\eta(1440) \to \gamma\rho^0$.

$\Gamma(\gamma\eta(1440) \to \gamma\eta\pi^+\pi^-)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.38±0.33±0.64		[34] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.0 ±0.6 ±1.1	261	[35] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$

[34] Via $a_0(980)\pi$.

[35] Includes unknown branching fraction to $\eta\pi^+\pi^-$.

$\Gamma(\gamma\rho\rho)/\Gamma_{total}$ — Γ_{98}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
4.5 ±0.8 OUR AVERAGE					
4.7 ±0.3 ±0.9		[36] BALTRUSAIT...86B		MRK3	$J/\psi \to 4\pi\gamma$
3.75±1.05±1.20		[37] BURKE	82	MRK2	$J/\psi \to 4\pi\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.09	90	[38] BISELLO	89B		$J/\psi \to 4\pi\gamma$

[36] 4π mass less than 2.0 GeV.

[37] 4π mass less than 2.0 GeV, $2\rho^0$ corrected to 2ρ by factor of 3.

[38] 4π mass in the range 2.0–25 GeV.

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{99}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.31±0.30 OUR AVERAGE					
4.50±0.14±0.53		BOLTON	92B	MRK3	$J/\psi \to \gamma\pi^+\pi^-\eta, \eta \to \gamma\gamma$
4.30±0.31±0.71		BOLTON	92B	MRK3	$J/\psi \to \gamma\pi^+\pi^-\eta, \eta \to \pi^+\pi^-\pi^0$
4.04±0.16±0.85	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
4.39±0.09±0.66	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
4.1 ±0.3 ±0.6		BLOOM	83	CBAL	$e^+e^- \to 3\gamma +$ hadronsγ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.9 ±1.1	6	BRANDELIK	79C	DASP	$e^+e^- \to 3\gamma$
2.4 ±0.7	57	BARTEL	76	CNTR	$e^+e^- \to 2\gamma\rho$

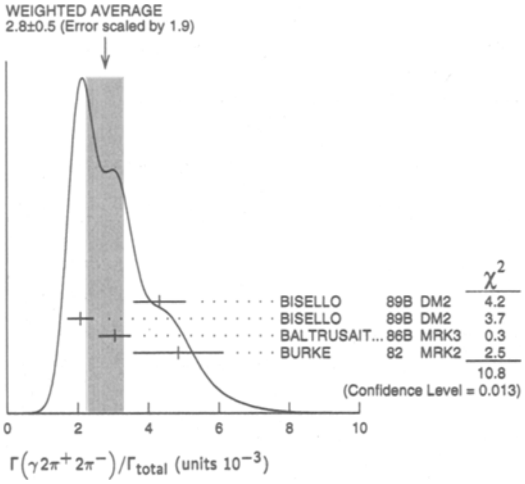
$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{total}$ — Γ_{100}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.8 ±0.5 OUR AVERAGE Error includes scale factor of 1.9. See the ideogram below.				
4.32±0.14±0.73	[39] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
2.08±0.13±0.35	[40] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
3.05±0.08±0.45	[40] BALTRUSAIT...86B		MRK3	$J/\psi \to 4\pi\gamma$
4.85±0.45±1.20	[41] BURKE	82	MRK2	e^+e^-

[39] 4π mass less than 3.0 GeV.

[40] 4π mass less than 2.0 GeV.

[41] 4π mass less than 2.5 GeV.



$\Gamma(\gamma f_4(2050))/\Gamma_{total}$ — Γ_{101}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.7±0.5±0.5	[42] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma\pi^+\pi^-$

[42] Assuming branching fraction $f_4(2050) \to \pi\pi$/ total = 0.167.

$\Gamma(\gamma\omega\omega)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.33 OUR AVERAGE					
1.41±0.2 ±0.42	120± 17	BISELLO	87	SPEC	e^+e^-, hadronsγ
1.76±0.09±0.45		BALTRUSAIT...85C		MRK3	$e^+e^- \to$ hadronsγ

$\Gamma(\gamma\eta(1440) \to \gamma\rho^0\rho^0)/\Gamma_{total}$ — Γ_{103}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.7 ±0.4 OUR AVERAGE Error includes scale factor of 1.3.				
2.1 ±0.4	BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1.36±0.38	[43,44] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[43] Estimated by us from various fits.

[44] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{104}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.38±0.14 OUR AVERAGE						
1.33±0.05±0.20		[45] AUGUSTIN	87	DM2		$J/\psi \to \gamma\pi^+\pi^-$
1.36±0.09±0.23		[45] BALTRUSAIT...87		MRK3		$J/\psi \to \gamma\pi^+\pi^-$
1.48±0.25±0.30	178	EDWARDS	82B	CBAL		$e^+e^- \to 2\pi^0\gamma$
2.0 ±0.7	35	ALEXANDER	78	PLUT	0	e^+e^-
1.2 ±0.6	30	[46] BRANDELIK	78B	DASP		$e^+e^- \to \pi^+\pi^-\gamma$

[45] Estimated using $B(f_2(1270) \to \pi\pi)=0.843 \pm 0.012$. The errors do not contain the uncertainty in the $f_2(1270)$ decay.

[46] Restated by us to take account of spread of E1, M2, E3 transitions.

$\Gamma(\gamma f_J(1710) \to \gamma K\overline{K})/\Gamma_{total}$ — Γ_{105}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
$8.5^{+1.2}_{-0.9}$ OUR AVERAGE Error includes scale factor of 1.2.					
$5.0\pm0.8^{+1.8}_{-0.4}$		[47,48] BAI	96C	BES	$J/\psi \to \gamma K^+K^-$
9.2±1.4±1.4		[48] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
10.4±1.2±1.6		[48] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
9.6±1.2±1.8		[48] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.6\pm0.2^{+0.6}_{-0.2}$		[48,49] BAI	96C	BES	$J/\psi \to \gamma K^+K^-$
< 0.8	90	[50] BISELLO	89B		$J/\psi \to 4\pi\gamma$
1.6±0.4±0.3		[51] BALTRUSAIT...87		MRK3	$J/\psi \to \gamma\pi^+\pi^-$
3.8±1.6		[52] EDWARDS	82D	CBAL	$e^+e^- \to \eta\eta\gamma$

[47] Assuming $J^P = 2^+$ for $f_J(1710)$.

[48] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$. We have multiplied K^+K^- measurement by 2, and $K^0_S K^0_S$ by 4 to obtain $K\overline{K}$ result.

[49] Assuming $J^P = 0^+$ for $f_J(1710)$.

[50] Includes unknown branching fraction to $\rho^0\rho^0$.

[51] Includes unknown branching fraction to $\pi^+\pi^-$.

[52] Includes unknown branching fraction to $\eta\eta$.

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{106}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.86±0.08 OUR AVERAGE					
0.88±0.08±0.11		BLOOM	83	CBAL	e^+e^-
0.82±0.10		BRANDELIK	79C	DASP	e^+e^-
1.3 ±0.4	21	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma f_1(1420) \to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{107}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.83±0.15 OUR AVERAGE				
0.76±0.15±0.21	[53,54] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$0.87\pm0.14^{+0.14}_{-0.11}$	[53] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$

[53] Included unknown branching fraction $f_1(1420) \to K\overline{K}\pi$.

[54] From fit to the $K^*(892)K\ 1^{++}$ partial wave.

$\Gamma(\gamma f_1(1285))/\Gamma_{total}$ — Γ_{108}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.65 ±0.10 OUR AVERAGE				
0.625±0.063±0.103	[55] BOLTON	92	MRK3	$J/\psi \to \gamma f_1(1285)$
0.70 ±0.08 ±0.16	[56] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$

[55] Obtained summing the sequential decay channels
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \pi\pi\pi\pi) = (1.44 \pm 0.39 \pm 0.27) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \delta\pi, \delta \to \eta\pi) = (3.90 \pm 0.42 \pm 0.87) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \delta\pi, \delta \to K\overline{K}) = (0.66 \pm 0.26 \pm 0.29) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \gamma\rho^0) = (0.25 \pm 0.07 \pm 0.03) \times 10^{-4}$.

[56] Using $B(f_1(1285) \to a_0(980)\pi) = 0.37$, and including unknown branching ratio for $a_0(980) \to \eta\pi$.

$\Gamma(\gamma f_2'(1525))/\Gamma_{\text{total}}$ Γ_{109}/Γ

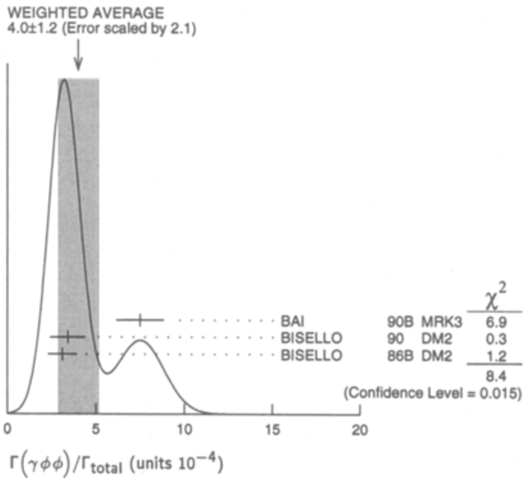
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$0.47^{+0.07}_{-0.06}$ OUR AVERAGE					
$0.36\pm0.04^{+0.14}_{-0.04}$			[57] BAI 96C	BES	$J/\psi \to \gamma K^+ K^-$
$0.56\pm0.14\pm0.09$			[57] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+ K^-$
$0.45\pm0.04\pm0.09$			[57] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$0.68\pm0.16\pm0.14$			[57] BALTRUSAIT...87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.34	90	4	[58] BRANDELIK 79C	DASP	$e^+ e^- \to \pi^+ \pi^- \gamma$
<0.23	90	3	ALEXANDER 78	PLUT	$e^+ e^- \to K^+ K^- \gamma$

[57] Using $B(f_2'(1525) \to K\overline{K}) = 0.888$.
[58] Assuming isotropic production and decay of the $f_2'(1525)$ and isospin.

$\Gamma(\gamma\phi\phi)/\Gamma_{\text{total}}$ Γ_{110}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
4.0 ± 1.2 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.				
$7.5\pm0.6\pm1.2$	168	BAI 90B	MRK3	$J/\psi \to \gamma 4K$
$3.4\pm0.8\pm0.6$	33 ± 7	[59] BISELLO 90	DM2	$J/\psi \to \gamma K^+ K^- K^0_S K^0_L$
$3.1\pm0.7\pm0.4$		[59] BISELLO 86B	DM2	$J/\psi \to \gamma K^+ K^- K^+ K^-$

[59] $\phi\phi$ mass less than 2.9 GeV, η_c excluded.



$\Gamma(\gamma p\overline{p})/\Gamma_{\text{total}}$ Γ_{111}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$0.38\pm0.07\pm0.07$		49	EATON 84	MRK2	$e^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	90		PERUZZI 78	MRK1	$e^+ e^-$

$\Gamma(\gamma\eta(2225))/\Gamma_{\text{total}}$ Γ_{112}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
0.29 ± 0.06 OUR AVERAGE			
$0.33\pm0.08\pm0.05$	[60] BAI 90B	MRK3	$J/\psi \to \gamma K^+ K^- K^+ K^-$
$0.27\pm0.06\pm0.06$	[60] BAI 90B	MRK3	$J/\psi \to \gamma K^+ K^- K^0_S K^0_L$
$0.24^{+0.15}_{-0.10}$	[61,62] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

[60] Includes unknown branching fraction to $\phi\phi$.
[61] Estimated by us from various fits.
[62] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\eta(1760) \to \gamma\rho^0\rho^0)/\Gamma_{\text{total}}$ Γ_{113}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
0.13 ± 0.09	[63,64] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$

[63] Estimated by us from various fits.
[64] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\pi^0)/\Gamma_{\text{total}}$ Γ_{114}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.039 ± 0.013 OUR AVERAGE				
$0.036\pm0.011\pm0.007$		BLOOM 83	CBAL	$e^+ e^-$
0.073 ± 0.047	10	BRANDELIK 79C	DASP	$e^+ e^-$

$\Gamma(\gamma p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{115}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.79	90	EATON 84	MRK2	$e^+ e^-$

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{116}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.5	90	BARTEL 77	CNTR	$e^+ e^-$

$\Gamma(\gamma\Lambda\overline{\Lambda})/\Gamma_{\text{total}}$ Γ_{117}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.13	90	HENRARD 87	DM2	$e^+ e^-$

$\Gamma(3\gamma)/\Gamma_{\text{total}}$ Γ_{118}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.055	90	PARTRIDGE 80	CBAL	$e^+ e^-$

$\Gamma(\gamma f_0(2200))/\Gamma_{\text{total}}$ Γ_{119}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.5	[65] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^0_S K^0_S$

[65] Includes unknown branching fraction to $K^0_S K^0_S$.

$\Gamma(\gamma f_J(2220))/\Gamma_{\text{total}}$ Γ_{120}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
>250	99.9		[66] HASAN 96	SPEC	$\overline{p}p \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>300			[67] BAI 96B	BES	$e^+ e^- \to \gamma\overline{p}p,\ K\overline{K}$
$<\ 2.3$	95		[68] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+ K^-$
$<\ 1.6$	95		[68] AUGUSTIN 88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$12.4^{+6.4}_{-5.2}\pm2.8$		23	[68] BALTRUSAIT...86D	MRK3	$J/\psi \to \gamma K^0_S K^0_S$
$8.4^{+3.4}_{-2.8}\pm1.6$		93	[68] BALTRUSAIT...86D	MRK3	$J/\psi \to \gamma K^+ K^-$

[66] Using BAI 96B.
[67] Using BARNES 93.
[68] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$.

$\Gamma(\gamma f_0(1500))/\Gamma_{\text{total}}$ Γ_{121}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
5.7 ± 0.8	[69,70] BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$

[69] Including unknown branching ratio for $f_0(1500) \to \pi^+\pi^-\pi^+\pi^-$.
[70] Assuming that $f_0(1500)$ decays only to two S-wave dipions.

$\Gamma(\gamma e^+ e^-)/\Gamma_{\text{total}}$ Γ_{122}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$8.8\pm1.3\pm0.4$	[71] ARMSTRONG 96	E760	$\overline{p}p \to e^+ e^- \gamma$

[71] For $E_\gamma > 100$ MeV.

$J/\psi(1S)$ REFERENCES

ARMSTRONG	96	PR D54 7067	+Bettoni+	(FNAL, FERR, GENO, UCI, NEAS, PENN, TORI)
BAI	96B	PRL 76 3502	+Chen, Chen+	(BES Collab.)
BAI	96C	PRL 77 3959	J.Z. Bai+	(BES Collab.)
BAI	96D	PR D54 1221	J.Z. Bai, Bardon+	(BES Collab.)
GRIBUSHIN	96	PR D53 4723	+Abramov, Antipov+	(E672 Collab., E706 Collab.)
HASAN	96	PL B388 376	+Bugg	(BRUN, LOQM)
BAI	95B	PL B355 374	+Chen, Chen+	(BES Collab.)
BUGG	95	PL B353 378	+Scott, Zoll+	(LOQM, PNPI, WASH)
ANTONELLI	93	PL B301 317	+Baldini+	(FENICE Collab.)
ARMSTRONG	93B	PR D47 772	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
BARNES	93	PL B309 469	+Birien, Breunlich	(PS185 Collab.)
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)
BOLTON	92	PL B278 495	+Brown, Bunnell+	(Mark III Collab.)
BOLTON	92B	PRL 69 1328	+Brown, Bunnell+	(Mark III Collab.)
COFFMAN	92	PRL 68 282	+DeJongh, Dubois, Hitlin+	(Mark III Collab.)
HSUEH	92	PR D45 R2181	+Palestini	(FNAL, TORI)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
BISELLO	90	PL B241 617	+Busetto+	(DM2 Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
JOUSSET	90	PR D41 1389	+Ajaltouni+	(DM2 Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
COFFMAN	88	PR D38 2695	+Dubois, Eigen, Hauser+	(Mark III Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BAGLIN	87	NP B286 592	+	(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)
BISELLO	87	PL B192 239	+Ajaltouni, Baldini+	(PADO, CLER, FRAS, LALO)
HENRARD	87	NP B292 670	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
PALLIN	87	NP B292 653	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)

BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
BALTRUSAIT...	85C	PRL 55 1723	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	85D	PR D32 566	Baltrusaitis, Coffman+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	84	PRL 52 2126	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
EATON	84	PR D29 804	+Goldhaber, Abrams, Alam, Boyarski+	(LBL, SLAC)
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
BURKE	82	PRL 49 632	+Trilling, Abrams, Alam, Blocker+	(LBL, SLAC)
EDWARDS	82B	PR D25 3065	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EDWARDS	82D	PRL 48 458	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	ARNS 33 143	Bloom, Peck	(SLAC, CIT)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
BESCH	81	ZPHY C8 1	+Eisermann, Lohr, Kowalski+	(BONN, DESY, MANZ)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
PARTRIDGE	80	PRL 44 712	+Peck+	(CIT, HARV, PRIN, SLAC, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
ALEXANDER	78	PL 72B 493	+Criegee+	(DESY, HAMB, SIEG, WUPP)
BESCH	78	PL 78B 347	+Eisermann, Kowalski, Eyss+	(BONN, DESY, MANZ)
BRANDELIK	78B	PL 74B 292	+Cords+	(DASP Collab.)
PERUZZI	78	PR D17 2901	+Piccolo, Alam, Boyarski, Goldhaber+	(SLAC, LBL)
BARTEL	77	PL 66B 489	+Duinker, Olsson, Heintze+	(DESY, HEIDP)
BURMESTER	77D	PL 72B 135	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
VANNUCCI	77	PR D15 1814	+Abrams, Alam, Boyarski+	(SLAC, LBL)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEIDP)
BRAUNSCH...	76	PL 63B 487	Braunschweig+	(DASP Collab.)
JEAN-MARIE	76	PRL 36 291	+Abrams, Boyarski, Breidenbach+	(SLAC, LBL) IG
BALDINI-...	75	PL 58B 471	Baldini-Celio, Bozzo, Capon+	(FRAS, ROMA)
BOYARSKI	75	PRL 34 1357	+Breidenbach, Bulos, Feldman+	(SLAC, LBL) JPC
DASP	75	PL 56B 491	Braunschweig, Konigs+	(DASP Collab.)
ESPOSITO	75B	LNC 14 73	+Bartoli, Bisello+	(FRAS, NAPL, PADO, ROMA)
FORD	75	PRL 34 604	+Beron, Hilger, Hofstadter+	(SLAC, PENN)

OTHER RELATED PAPERS

HOU	97	PR D55 6952	Wei-Shu Hou	
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)
ASH	74	LNC 11 705	+Zorn, Bartoli+	(FRAS, UMD, NAPL, PADO, ROMA)
AUBERT	74	PRL 33 1404	+Becker, Biggs, Burger, Chen, Everhart	(MIT, BNL)
AUGUSTIN	74	PRL 33 1406	+Boyarski, Abrams, Briggs+	(SLAC, LBL)
BACCI	74	PRL 33 1408	+Bartoli, Barbarino, Barbiellini+	(FRAS)
Also	74B	PRL 33 1649	Bacci	
BALDINI-...	74	LNC 11 711	Baldini-Celio, Bacci+	(FRAS, ROMA)
BARBIELLINI	74	LNC 11 718	+Bemporad+	(FRAS, NAPL, PISA, ROMA)
BRAUNSCH...	74	PL 53B 393	Braunschweig+	(DASP Collab.)
CHRISTENS...	70	PRL 25 1523	Christenson, Hicks, Lederman+	(COLU, BNL, CERN)

$\boxed{\chi_{c0}(1P)}$

$I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3417.3± 2.8 OUR AVERAGE				
3417.8± 0.4±4	[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3422 ±10	[2] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3416 ± 3 ±4	[2] TANENBAUM	78	MRK1	e^+e^-
3415 ± 9	[2] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.

[2] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

$\chi_{c0}(1P)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
13.5±3.3±4.2	GAISER	86	CBAL	$\psi(2S) \to \gamma X, \gamma\pi^0\pi^0$

$\chi_{c0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(3.7 ± 0.7) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(3.0 ± 0.7) %	
Γ_3	$\rho^0\pi^+\pi^-$	(1.6 ± 0.5) %	
Γ_4	$3(\pi^+\pi^-)$	(1.5 ± 0.5) %	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(1.2 ± 0.4) %	
Γ_6	$\pi^+\pi^-$	$(7.5\pm2.1)\times10^{-3}$	
Γ_7	K^+K^-	$(7.1\pm2.4)\times10^{-3}$	
Γ_8	$\pi^+\pi^-p\overline{p}$	$(5.0\pm2.0)\times10^{-3}$	
Γ_9	$\pi^0\pi^0$		
Γ_{10}	$\eta\eta$		
Γ_{11}	$p\overline{p}$	$< 9.0 \times10^{-4}$	90%
	Radiative decays		
Γ_{12}	$\gamma J/\psi(1S)$	$(6.6\pm1.8)\times10^{-3}$	
Γ_{13}	$\gamma\gamma$	$< 5 \times10^{-4}$	95%

$\chi_{c0}(1P)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{13}

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
< 6.2	95	CHEN	90B	CLEO	$e^+e^- \to e^+e^-\chi_{c0}$
4.0±2.8		LEE	85	CBAL	$\psi' \to$ photons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	95	AIHARA	88D	TPC	$e^+e^- \to e^+e^-X$

$\chi_{c0}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.037±0.007	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.030±0.007	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.005	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.015±0.005	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.004	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
75±21 OUR AVERAGE				
70±30	[3] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
80±30	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
71±24 OUR AVERAGE				
60±30	[3] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
90±40	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.005 ±0.002	[3] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.1±0.4±0.5	[4] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.5±0.8±0.8	[4] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<9.0	90	[3] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$

[3] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

[4] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.093 \pm 0.008$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
66± 18 OUR AVERAGE				
60± 18	GAISER	86	CBAL	$\psi(2S) \to \gamma\chi_{c0}$
320±210	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
150±100	[5] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c0}$
210±210	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.0±2.0±1.1	[4] LEE	85	CBAL	$\psi' \to$ photons

[5] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c0}(1P)$ REFERENCES

CHEN 90B PL B243 169 +McIlwain+ (CLEO Collab.)
AIHARA 88D PRL 60 2355 +Alston-Garnjost+ (TPC Collab.)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
LEE 85 SLAC 282 (SLAC)
BRANDELIK 79B NP B160 426 +Cords+ (DASP Collab.)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEIDP)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
Also 82 Private Comm. Trilling (LBL, UCB)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)

OTHER RELATED PAPERS

OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
FELDMAN 75B PRL 35 821 +Jean-Marie, Sadoulet, Vannucci+ (LBL, SLAC)
Also 75C PRL 35 1189 Feldman
Erratum.
TANENBAUM 75 PRL 35 1323 +Whitaker, Abrams+ (LBL, SLAC)

$\chi_{c1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$

$\chi_{c1}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3510.53± 0.12 OUR AVERAGE					
3510.53± 0.04±0.12	513	ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$
3511.3 ± 0.4 ±0.4	30	BAGLIN	86B	SPEC	$\overline{p}p \to e^+e^-X$
3512.3 ± 0.3 ±4.0		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3507.4 ± 1.7	91	[2] LEMOIGNE	82	GOLI	$190\ \pi^-\mathrm{Be} \to \gamma 2\mu$
3510.4 ± 0.6		OREGLIA	82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3510.1 ± 1.1	254	[3] HIMEL	80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3509 ±11	21	BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3507 ± 3		[3] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3505.0 ± 4 ±4		[3,4] TANENBAUM	78	MRK1	e^+e^-
3513 ± 7	367	[3] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3500 ±10	40	TANENBAUM	75	MRK1	Hadrons γ

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.

[2] $J/\psi(1S)$ mass constrained to 3097 MeV.

[3] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[4] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c1}(1P)$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.88±0.11±0.08		513	ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	95		BAGLIN	86B	SPEC	$\overline{p}p \to e^+e^-X$
<3.8	90		GAISER	86	CBAL	$\psi(2S) \to \gamma X$

$\chi_{c1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
	Hadronic decays	
Γ_1	$3(\pi^+\pi^-)$	(2.2±0.8) %
Γ_2	$2(\pi^+\pi^-)$	(1.6±0.5) %
Γ_3	$\pi^+\pi^-K^+K^-$	(9 ±4) × 10^{-3}
Γ_4	$\rho^0\pi^+\pi^-$	(3.9±3.5) × 10^{-3}
Γ_5	$K^+\overline{K}^*(892)^0\pi^- +$ c.c.	(3.2±2.1) × 10^{-3}
Γ_6	$\pi^+\pi^-p\overline{p}$	(1.4±0.9) × 10^{-3}
Γ_7	$p\overline{p}$	(8.6±1.2) × 10^{-5}
Γ_8	$\pi^+\pi^- + K^+K^-$	< 2.1 × 10^{-3}
	Radiative decays	
Γ_9	$\gamma J/\psi(1S)$	(27.3±1.6) %
Γ_{10}	$\gamma\gamma$	

$\chi_{c1}(1P)$ PARTIAL WIDTHS

$\Gamma(p\overline{p})$ Γ_7

VALUE (eV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
74± 9 OUR AVERAGE					
76±10±5	513	[5] ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$
69^{+16}_{-13}±4		[5] BAGLIN	86B	SPEC	$\overline{p}p \to e^+e^-X$

[5] Restated by us using $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0171 \pm 0.0011$.

$\chi_{c1}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\mathrm{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.022±0.008	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\mathrm{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.016±0.005	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\mathrm{total}}$ Γ_3/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
90±40	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\mathrm{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
39±35	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \mathrm{c.c.})/\Gamma_{\mathrm{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
32±21	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\mathrm{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
14±9	[6] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(p\overline{p})/\Gamma_{\mathrm{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.86±0.12		513	[7] ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 0.54	95		BAGLIN	86B	SPEC	$\overline{p}p \to e^+e^-X$
<12.0	90		[6] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{\mathrm{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<21		[6] FELDMAN	77	MRK1	$\psi(2S) \to \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<38	90	[6] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$

[6] Estimated using $B(\psi(2S) \to \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

[7] Restated by us using $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0171 \pm 0.0011$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{\mathrm{total}}$ Γ_9/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.273±0.016 OUR AVERAGE					
0.284±0.021		GAISER	86	CBAL	$\psi(2S) \to \gamma X$
0.274±0.046	943	[8] OREGLIA	82	CBAL	$\psi(2S) \to \gamma\chi_{c1}$
0.28 ±0.07		[8] HIMEL	80	MRK2	$\psi(2S) \to \gamma\chi_{c1}$
0.19 ±0.05		[8] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c1}$
0.29 ±0.05		[8] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c1}$
0.28 ±0.09		[8] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.57 ±0.17		[8] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{\mathrm{total}}$ Γ_{10}/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0015	90	[8] YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[8] Estimated using $B(\psi(2S) \to \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c1}(1P)$ REFERENCES

ARMSTRONG 92 NP B373 35 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
Also 92B PRL 68 1468 Armstrong, Bettoni+(FNAL, FERR, GENO, UCI, NWES+)
BAGLIN 86B PL B172 455 (LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
LEMOIGNE 82 PL 113B 509 +Barate, Astbury+ (SACL, LOIC, SHMP, IND)
OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
Also 82B Private Comm. Oreglia (EFI)
HIMEL 80 PRL 44 920 +Abrams, Alam, Blocker+ (LBL, SLAC)
Also 82 Private Comm. Trilling (LBL, UCB)
BRANDELIK 79B NP B160 426 +Cords+ (DASP Collab.)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEIDP)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
Also 82 Private Comm. Trilling (LBL, UCB)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN 77 PRPL 33C 285 +Perl (LBL, SLAC)
YAMADA 77 Hamburg Conf. 69 (DASP Collab.)
TANENBAUM 75 PRL 35 1323 +Whitaker, Abrams+ (LBL, SLAC)

OTHER RELATED PAPERS

BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
BRAUNSCH... 75B PL 57B 407 Braunschweig, Konigs+ (DASP Collab.)
SIMPSON 75 PRL 35 699 +Beron, Ford, Hilger, Hofstadter+ (STAN, PENN)

$h_c(1P)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$h_c(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3526.14±0.24 OUR AVERAGE				
3526.20±0.15±0.20	59	ARMSTRONG 92D	E760	$\bar{p}p \to J/\psi\pi^0$
3525.4 ±0.8 ±0.4	5	BAGLIN 86	SPEC	$\bar{p}p \to J/\psi X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3527 ±8	42	ANTONIAZZI 94	E705	300 $\pi^\pm$, $pLi \to J/\psi\pi^0 X$

$h_c(1P)$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.1	90	59	ARMSTRONG 92D	E760	$\bar{p}p \to J/\psi\pi^0$

$h_c(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\pi^0$	seen
Γ_2	$J/\psi(1S)\pi\pi$	not seen
Γ_3	$p\bar{p}$	

$\Gamma(J/\psi(1S)\pi\pi)/\Gamma(J/\psi(1S)\pi^0)$ — Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.18	90	ARMSTRONG 92D	E760	$\bar{p}p \to J/\psi\pi^0$

$h_c(1P)$ REFERENCES

ANTONIAZZI	94	PR D50 4258	+Arenton+	(E705 Collab.)
ARMSTRONG	92D	PRL 69 2337	+Bettoni+	(FNAL, FERR, GENO, UCI, PENN, TORI)
BAGLIN	86	PL B171 135	+Baird+	(LAPP, CERN, TORI, STRB, OSLO, ROMA+)

$\chi_{c2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3556.17± 0.13 OUR AVERAGE				
3556.15± 0.07±0.12	585	ARMSTRONG 92	E760	$\bar{p}p \to e^+e^-\gamma$
3556.9 ± 0.4 ±0.5	50	BAGLIN 86B	SPEC	$\bar{p}p \to e^+e^-X$
3557.8 ± 0.2 ±4		[1] GAISER 86	CBAL	$\psi(2S) \to \gamma X$
3553.4 ± 2.2	66	[2] LEMOIGNE 82	GOLI	190 π^- Be $\to \gamma 2\mu$
3555.9 ± 0.7		[3] OREGLIA 82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3557 ± 1.5	69	[4] HIMEL 80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3551 ±11	15	BRANDELIK 79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3553 ± 4		[4] BARTEL 78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3553 ± 4 ±4		[4,5] TANENBAUM 78	MRK1	e^+e^-
3563 ± 7	360	[4] BIDDICK 77	CNTR	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3543 ±10	4	WHITAKER 76	MRK1	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.

[2] $J/\psi(1S)$ mass constrained to 3097 MeV.

[3] Assuming $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[4] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[5] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c2}(1P)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.00±0.18 OUR AVERAGE				
1.98±0.17±0.07	585	ARMSTRONG 92	E760	$\bar{p}p \to e^+e^-\gamma$
$2.6\ ^{+1.4}_{-1.0}$	50	BAGLIN 86B	SPEC	$\bar{p}p \to e^+e^-X$
$2.8\ ^{+2.1}_{-2.0}$		[6] GAISER 86	CBAL	$\psi(2S) \to \gamma X$

[6] Errors correspond to 90% confidence level; authors give only width range.

$\chi_{c2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(2.2±0.5) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(1.9±0.5) %	
Γ_3	$3(\pi^+\pi^-)$	(1.2±0.8) %	
Γ_4	$\rho^0\pi^+\pi^-$	(7 ±4) × 10^{-3}	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(4.8±2.8) × 10^{-3}	
Γ_6	$\pi^+\pi^-p\bar{p}$	(3.3±1.3) × 10^{-3}	
Γ_7	$\pi^+\pi^-$	(1.9±1.0) × 10^{-3}	
Γ_8	K^+K^-	(1.5±1.1) × 10^{-3}	
Γ_9	$p\bar{p}$	(10.0±1.0) × 10^{-5}	
Γ_{10}	$\pi^0\pi^0$		
Γ_{11}	$\eta\eta$		
Γ_{12}	$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%
	Radiative decays		
Γ_{13}	$\gamma J/\psi(1S)$	(13.5±1.1) %	
Γ_{14}	$\gamma\gamma$	(1.6±0.5) × 10^{-4}	

$\chi_{c2}(1P)$ PARTIAL WIDTHS

$\Gamma(p\bar{p})$ — Γ_9

VALUE (eV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
206±22 OUR AVERAGE				
197±18±16	585	[7] ARMSTRONG 92	E760	$\bar{p}p \to e^+e^-\gamma$
$252^{+55}_{-48}\pm21$		[7] BAGLIN 86B	SPEC	$\bar{p}p \to e^+e^-X$

[7] Restated by us using $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0085 \pm 0.0007$.

$\Gamma(\gamma\gamma)$ — Γ_{14}

VALUE (keV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.37 ±0.17 OUR AVERAGE		Error includes scale factor of 1.9.		
1.08 ±0.30 ±0.26		DOMINICK 94	CLE2	$e^+e^- \to e^+e^-\chi_{c2}$
0.321±0.078±0.054		[8] ARMSTRONG 93	E760	$\bar{p}p \to \gamma\gamma$
3.4 ±1.7 ±0.9		BAUER 93	TPC	$e^+e^- \to e^+e^-\chi_{c2}$
$2.9\ ^{+1.3}_{-1.0}\ \pm1.7$		BAGLIN 87B	SPEC	$\bar{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.2	95	UEHARA 91	VNS	$e^+e^- \to e^+e^-\chi_{c2}$
<1.0	95	CHEN 90B	CLEO	$e^+e^- \to e^+e^-\chi_{c2}$
<4.2	95	AIHARA 88D	TPC	$e^+e^- \to e^+e^-X$

[8] Using $B(\chi_{c2}(1P) \to p\bar{p}) = (1.00 \pm 0.23) \times 10^{-4}$ and $\Gamma_{total} = 2.00 \pm 0.18$ MeV.

$\chi_{c2}(1P)$ BRANCHING RATIOS

—— HADRONIC DECAYS ——

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.022±0.006	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.019±0.005	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_3/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.012±0.008	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
68±40	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
48±28	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^- p\bar{p})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
33±13	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.9±1.0	4	[9] BRANDELIK 79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$[\Gamma(\pi^+\pi^-)+\Gamma(K^+K^-)]/\Gamma_{total}$ — $(\Gamma_7+\Gamma_8)/\Gamma$

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
24±10	[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.5±1.1	2	[9] BRANDELIK 79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(p\bar{p})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
1.00±0.10 OUR AVERAGE					
1.00±0.11		585	[10] ARMSTRONG 92	E760	$\bar{p}p \to e^+e^-\gamma$
$0.97^{+0.44}_{-0.28}\pm0.08$			BAGLIN 86B	SPEC	$\bar{p}p \to e^+e^-X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.5	90		[9] BRANDELIK 79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\bar{p} \to \chi_{c2}(1P) \to \gamma\gamma$ — $\Gamma_9\Gamma_{14}/\Gamma^2$

VALUE (units 10^{-7})	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.160±0.039±0.016		ARMSTRONG 93	E760	$\bar{p}p \to \gamma\gamma$
$0.99\ ^{+0.46}_{-0.35}$	6	[11] BAGLIN 87B	SPEC	$\bar{p}p \to \gamma\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.1±0.2±0.2	[12] LEE 85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
7.9±4.1±2.4	[12] LEE 85	CBAL	$\psi' \to$ photons

$\Gamma(J/\psi(1S)\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	BARATE 81	SPEC	190 GeV π^- Be $\to 2\pi 2\mu$

[9] Estimated using B($\psi(2S) \to \gamma\chi_{c2}(1P)$) = 0.078; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

[10] Restated by us using B($\chi_{c2}(1P) \to J/\psi(1S)\gamma$)B($J/\psi(1S) \to e^+e^-$) = 0.0085 ± 0.0007.

[11] Assuming isotropic $\chi_{c2}(1P) \to \gamma\gamma$ distribution.

[12] LEE 85 result is calculated using B($\psi(2S) \to \gamma\chi_{c2}(1P)$) = 0.078 ± 0.008.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.136±0.011 OUR AVERAGE				
0.124±0.015		GAISER 86	CBAL	$\psi(2S) \to \gamma X$
0.162±0.028	479	[13] OREGLIA 82	CBAL	$\psi(2S) \to \gamma\chi_{c2}$
0.14 ±0.04		[13] HIMEL 80	MRK2	$\psi(2S) \to \gamma\chi_{c2}$
0.18 ±0.05		[13] BRANDELIK 79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.03		[13] BARTEL 78B	CNTR	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.08		[13] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28 ±0.13		[13] BIDDICK 77	CNTR	$\psi(2S) \to \gamma X$

[13] Estimated using B($\psi(2S) \to \gamma\chi_{c2}(1P)$) = 0.078; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
1.60±0.39±0.23	[14] ARMSTRONG 93	E760	$\bar{p}p \to \gamma\gamma$

[14] Using B($\chi_{c2}(1P) \to p\bar{p}$) = (1.00 ± 0.23) × 10^{-4}.

$\chi_{c2}(1P)$ REFERENCES

DOMINICK	94	PR D50 4265	+Sanghera+	(CLEO Collab.)
ARMSTRONG	93	PRL 70 2988	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
BAUER	93	PL B302 345	+Belcinski+	(TPC Collab.)
ARMSTRONG	92	NP B373 35	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
Also	92B	PRL 68 1468	Armstrong, Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
UEHARA	91	PL B266 188	+Abe+	(VENUS Collab.)
CHEN	90B	PL B243 169	+McIlwain+	(CLEO Collab.)
AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
BAGLIN	87B	PL B187 191	+Baird, Bassompierre, Borreani+	(R704 Collab.)
BAGLIN	86B	PL B172 455		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
Also	82B	Private Comm.	Oreglia	(EFI)
BARATE	81	PR D24 2994	+Astbury+	(SACL, LOIC, SHMP, CERN, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)

OTHER RELATED PAPERS

BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also Erratum.	75C	PRL 35 1189	Feldman	
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\boxed{\eta_c(2S)}$

$I^G(J^{PC}) = ?^?(?^{?+})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$\eta_c(2S)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3594±5	[1] EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

[1] Assuming mass of $\psi(2S)$ = 3686 MeV.

$\eta_c(2S)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.0	95	EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

$\eta_c(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen
Γ_2	$\gamma\gamma$	

$\eta_c(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.01	90	LEE 85	CBAL	$\psi' \to$ photons

$\eta_c(2S)$ REFERENCES

LEE	85	SLAC 282		(SLAC)
EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
PORTER	81	SLAC Summer Inst. 355	+Edwards+	(CIT, HARV, PRIN, STAN, SLAC)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)

$\psi(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(2S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3686.00±0.09 OUR AVERAGE					
3686.02±0.09±0.27		ARMSTRONG	93B	E760	$\bar{p}p \to e^+e^-$
3686.00±0.10	413	ZHOLENTZ	80	OLYA	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3684 ±2		GRIBUSHIN	96	FMPS	515 π^- Be $\to 2\mu X$
3683 ±5	77	ANTONIAZZI	94	E705	300 $\pi^\pm$, pLi $\to J/\psi\pi^+\pi^- X$

$m_{\psi(2S)} - m_{J/\psi(1S)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
589.07±0.13 OUR AVERAGE				
589.7 ±1.2	LEMOIGNE	82	GOLI	190 π^- Be $\to 2\mu$
589.07±0.13	[1] ZHOLENTZ	80	OLYA	e^+e^-
588.7 ±0.8	LUTH	75	MRK1	

[1] Redundant with data in mass above.

$\psi(2S)$ WIDTH

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
277±31 OUR AVERAGE Error includes scale factor of 1.1.				
306±36±16	ARMSTRONG	93B	E760	$\bar{p}p \to e^+e^-$
243±43	[2] PDG	92	RVUE	

[2] Uses $\Gamma(ee)$ from ALEXANDER 89 and $B(ee) = (88 \pm 13) \times 10^{-4}$ from FELDMAN 77.

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(98.10±0.30) %	
Γ_2	virtual$\gamma \to$ hadrons	(2.9 ±0.4) %	
Γ_3	e^+e^-	(8.5 ±0.7) $\times 10^{-3}$	
Γ_4	$\mu^+\mu^-$	(7.7 ±1.7) $\times 10^{-3}$	
	Decays into $J/\psi(1S)$and anything		
Γ_5	$J/\psi(1S)$anything	(54.2 ±3.0) %	
Γ_6	$J/\psi(1S)$neutrals	(22.8 ±1.7) %	
Γ_7	$J/\psi(1S)\pi^+\pi^-$	(30.2 ±1.9) %	
Γ_8	$J/\psi(1S)\pi^0\pi^0$	(17.9 ±1.8) %	
Γ_9	$J/\psi(1S)\eta$	(2.7 ±0.4) %	S=1.7
Γ_{10}	$J/\psi(1S)\pi^0$	(9.7 ±2.1) $\times 10^{-4}$	
Γ_{11}	$J/\psi(1S)\mu^+\mu^-$	(10.0 ±3.3) $\times 10^{-3}$	
	Hadronic decays		
Γ_{12}	$3(\pi^+\pi^-)\pi^0$	(3.5 ±1.6) $\times 10^{-3}$	
Γ_{13}	$2(\pi^+\pi^-)\pi^0$	(3.0 ±0.8) $\times 10^{-3}$	
Γ_{14}	$\pi^+\pi^-K^+K^-$	(1.6 ±0.4) $\times 10^{-3}$	
Γ_{15}	$\pi^+\pi^-p\bar{p}$	(8.0 ±2.0) $\times 10^{-4}$	
Γ_{16}	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(6.7 ±2.5) $\times 10^{-4}$	
Γ_{17}	$2(\pi^+\pi^-)$	(4.5 ±1.0) $\times 10^{-4}$	
Γ_{18}	$\rho^0\pi^+\pi^-$	(4.2 ±1.5) $\times 10^{-4}$	
Γ_{19}	$\bar{p}p$	(1.9 ±0.5) $\times 10^{-4}$	
Γ_{20}	$3(\pi^+\pi^-)$	(1.5 ±1.0) $\times 10^{-4}$	
Γ_{21}	$\bar{p}p\pi^0$	(1.4 ±0.5) $\times 10^{-4}$	
Γ_{22}	K^+K^-	(1.0 ±0.7) $\times 10^{-4}$	
Γ_{23}	$\pi^+\pi^-\pi^0$	(9 ±5) $\times 10^{-5}$	
Γ_{24}	$\rho\pi$	< 8.3 $\times 10^{-5}$	CL=90%
Γ_{25}	$\pi^+\pi^-$	(8 ±5) $\times 10^{-5}$	
Γ_{26}	$\Lambda\bar{\Lambda}$	< 4 $\times 10^{-4}$	CL=90%
Γ_{27}	$\Xi^-\bar{\Xi}^+$	< 2 $\times 10^{-4}$	CL=90%
Γ_{28}	$K^+K^-\pi^0$	< 2.96 $\times 10^{-5}$	CL=90%
Γ_{29}	$K^+\overline{K}^*(892)^-$ + c.c.	< 5.4 $\times 10^{-5}$	CL=90%
	Radiative decays		
Γ_{30}	$\gamma\chi_{c0}(1P)$	(9.3 ±0.9) %	
Γ_{31}	$\gamma\chi_{c1}(1P)$	(8.7 ±0.8) %	
Γ_{32}	$\gamma\chi_{c2}(1P)$	(7.8 ±0.8) %	
Γ_{33}	$\gamma\eta_c(1S)$	(2.8 ±0.6) $\times 10^{-3}$	
Γ_{34}	$\gamma\eta_c(2S)$		
Γ_{35}	$\gamma\pi^0$		
Γ_{36}	$\gamma\eta'(958)$	< 1.1 $\times 10^{-3}$	CL=90%
Γ_{37}	$\gamma\eta$		
Γ_{38}	$\gamma\gamma$	< 1.6 $\times 10^{-4}$	CL=90%
Γ_{39}	$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	< 1.2 $\times 10^{-4}$	CL=90%
	Mode needed for fitting purposes		
Γ_{40}	1. – other fit modes	(22.4 ±3.3) %	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 17 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 =$ 8.9 for 10 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_8	25						
x_9	2	−8					
x_{11}	19	5	0				
x_{30}	0	0	0	0			
x_{31}	2	−5	−1	0	0		
x_{32}	1	−2	0	0	0	0	
x_{40}	−75	−66	−10	−24	−26	−22	−23
	x_7	x_8	x_9	x_{11}	x_{30}	x_{31}	x_{32}

$\psi(2S)$ PARTIAL WIDTHS

Γ(hadrons) Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
224±56	LUTH	75	MRK1	e^+e^-

$\Gamma(e^+e^-)$ Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.14±0.21	ALEXANDER	89	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.3	BRANDELIK	79C	DASP	e^+e^-
2.1 ±0.3	[3] LUTH	75	MRK1	e^+e^-

[3] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$\Gamma(\gamma\gamma)$ Γ_{38}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRANDELIK	79C	DASP	e^+e^-

$\psi(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel$_i$ in the e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(i)$ or the branching ratio $\Gamma(i)$/total.

Γ(hadrons) × $\Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.2±0.4	ABRAMS	75	MRK1	e^+e^-

$\psi(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.981 ±0.003	[4] LUTH 75	MRK1	e^+e^-

$\Gamma(\text{virtual}\gamma \to \text{hadrons})/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.029±0.004	[5] LUTH 75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
85± 7 OUR AVERAGE			
83± 5±7	[6] ARMSTRONG 97	E760	$\overline{p}p \to \psi(2S)X$
88±13	[7] FELDMAN 77	RVUE	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
77±17	[8] HILGER 75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_4/Γ_3

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.89±0.16	BOYARSKI 75C	MRK1	e^+e^-

[4] Includes cascade decay into $J/\psi(1S)$.

[5] Included in $\Gamma(\text{hadrons})/\Gamma_{\text{total}}$.

[6] Using $B(J/\psi \to e^+e^-) = 0.0599$+-0.0025 and $B(\psi(2S) \to J/\psi(1S)\text{anything}) = 0.04$.

[7] From an overall fit assuming equal partial widths for e^+e^- and $\mu^+\mu^-$. For a measurement of the ratio see the entry $\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ below. Includes LUTH 75, HILGER 75, BURMESTER 77.

[8] Restated by us using $B(\psi(2S) \to J/\psi(1S)\text{anything}) = 0.55$.

DECAYS INTO $J/\psi(1S)$ AND ANYTHING

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{\text{total}}$ — $\Gamma_5/\Gamma = (\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{31}+0.135\Gamma_{32})/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.542±0.030 OUR FIT			
0.55 ±0.07 OUR AVERAGE			
0.51 ±0.12	BRANDELIK 79C	DASP	$e^+e^- \to \mu^+\mu^-X$
0.57 ±0.08	ABRAMS 75B	MRK1	$e^+e^- \to \mu^+\mu^-X$

$\Gamma(J/\psi(1S)\text{neutrals})/\Gamma_{\text{total}}$ — $\Gamma_6/\Gamma = (0.9761\Gamma_8+0.715\Gamma_9+0.273\Gamma_{31}+0.135\Gamma_{32})/\Gamma$

VALUE	*DOCUMENT ID*
0.228±0.017 OUR FIT	

$\Gamma(J/\psi(1S)\text{neutrals})/\Gamma(J/\psi(1S)\text{anything})$ — $\Gamma_6/\Gamma_5 = (0.9761\Gamma_8+0.715\Gamma_9+0.273\Gamma_{31}+0.135\Gamma_{32})/(\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{31}+0.135\Gamma_{32})$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.421±0.021 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.44 ±0.03	[9] ABRAMS 75B	MRK1	$e^+e^- \to J/\psi X$

$\Gamma(J/\psi(1S)\text{neutrals})/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — $\Gamma_6/\Gamma_7 = (0.9761\Gamma_8+0.715\Gamma_9+0.273\Gamma_{31}+0.135\Gamma_{32})/\Gamma_7$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.76±0.07 OUR FIT			
0.73±0.09	[9] TANENBAUM 76	MRK1	e^+e^-

$\Gamma(J/\psi(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.302±0.019 OUR FIT				
0.296±0.023 OUR AVERAGE				
0.283±0.021±0.020	363	[10] ARMSTRONG 97	E760	$\overline{p}p \to \psi(2S)X$
0.32 ±0.04		ABRAMS 75B	MRK1	$e^+e^- \to J/\psi\pi^+\pi^-$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.179±0.018 OUR FIT				
0.184±0.019±0.013	157	[10] ARMSTRONG 97	E760	$\overline{p}p \to \psi(2S)X$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — Γ_8/Γ_7

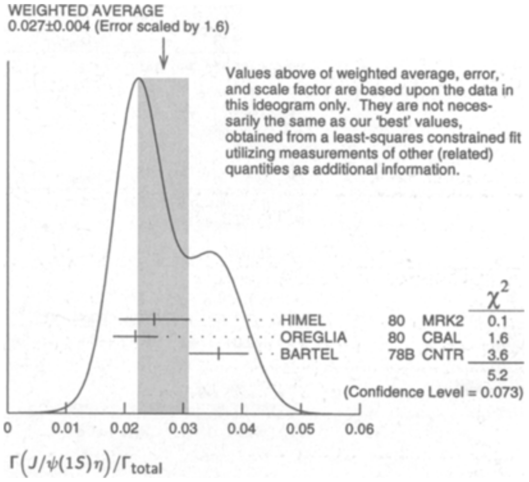
VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.59±0.06 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.53±0.06	[11] TANENBAUM 76	MRK1	e^+e^-
0.64±0.15	[12] HILGER 75	SPEC	e^+e^-

$\Gamma(J/\psi(1S)\pi^+\pi^-)/\Gamma(J/\psi(1S)\mu^+\mu^-)$ — Γ_7/Γ_{11}

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
30 ±10 OUR FIT			
30.2± 7.1±6.8	[13] GRIBUSHIN 96	FMPS	515 $\pi^-\text{Be} \to 2\mu X$

$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.027 ±0.004 OUR FIT Error includes scale factor of 1.7.				
0.027 ±0.004 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.				
0.025 ±0.006	166	HIMEL 80	MRK2	e^+e^-
0.0218±0.0014±0.0035	386	OREGLIA 80	CBAL	$e^+e^- \to J/\psi 2\gamma$
0.036 ±0.005	164	BARTEL 78B	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032 ±0.010 ±0.002	36	[14] ARMSTRONG 97	E760	$\overline{p}p \to \psi(2S)X$
0.035 ±0.009	17	[14] BRANDELIK 79B	DASP	$e^+e^- \to J/\psi 2\gamma$
0.043 ±0.008	44	[14] TANENBAUM 76	MRK1	e^+e^-



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
9.7±2.1 OUR AVERAGE				
15 ±6	7	HIMEL 80	MRK2	e^+e^-
9 ±2 ±1	23	OREGLIA 80	CBAL	$\psi(2S) \to J/\psi 2\gamma$

[9] The ABRAMS 75B measurement of Γ_6/Γ_5 and the TANENBAUM 76 result for Γ_6/Γ_7 are not independent. The TANENBAUM 76 result is used in the fit because it includes more accurate corrections for angular distributions.

[10] Using $B(J/\psi \to e^+e^-) = 0.0599$+-0.0025.

[11] Not independent of the TANENBAUM 76 result for Γ_6/Γ_7.

[12] Ignoring the $J/\psi(1S)\eta$ and $J/\psi(1S)\gamma\gamma$ decays.

[13] Using $B(J/\psi(1S) \to \mu^+\mu^-) = 0.0597 \pm 0.0025$.

[14] Low statistics data removed from average.

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
35±16	6	FRANKLIN 83	MRK2	$e^+e^- \to$ hadrons

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
30±8	42	FRANKLIN 83	MRK2	e^+e^-

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
16±4	[15] TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
8 ±2	[15] TANENBAUM 78	MRK1	e^+e^-

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
6.7±2.5	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
4.5±1.0	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
4.2±1.5	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(p\bar{p})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.9±0.5 OUR AVERAGE					
1.4±0.8	4	BRANDELIK	79C	DASP	e^+e^-
2.3±0.7		FELDMAN	77	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
1.5±1.0	[15] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(p\bar{p}\pi^0)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.4±0.5	9	FRANKLIN	83	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.0±0.7		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8±0.5		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.85±0.46	4	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(\Lambda\bar{\Lambda})/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<4	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\Xi^-\bar{\Xi}^+)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.83	90	1	FRANKLIN	83	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BARTEL	76	CNTR	e^+e^-
<10	90		[16] ABRAMS	75	MRK1	e^+e^-

$\Gamma(K^+K^-\pi^0)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2.96	90	1	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(K^+\bar{K}^*(892)^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{29}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<5.4	90	FRANKLIN	83	MRK2	$e^+e^- \rightarrow$ hadrons

[15] Assuming entirely strong decay.
[16] Final state $\rho^0\pi^0$.

RADIATIVE DECAYS

$\Gamma(\gamma\chi_{c0}(1P))/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
9.3±0.9 OUR FIT				
9.3±0.8 OUR AVERAGE				
9.9±0.5±0.8	[17] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.2±2.3	[17] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$
7.5±2.6	[17] WHITAKER	76	MRK1	e^+e^-

$\Gamma(\gamma\chi_{c1}(1P))/\Gamma_{\text{total}}$ Γ_{31}/Γ

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
8.7±0.8 OUR FIT				
8.7±0.8 OUR AVERAGE				
9.0±0.5±0.7	[18] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.1±1.9	[19] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\chi_{c2}(1P))/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
7.8±0.8 OUR FIT				
7.8±0.8 OUR AVERAGE				
8.0±0.5±0.7	[20] GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$
7.0±2.0	[19] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(1S))/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE (units 10^{-2})	*DOCUMENT ID*		*TECN*	*COMMENT*
0.28±0.06	GAISER	86	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(2S))/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE (units 10^{-2})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.2 to 1.3	95	EDWARDS	82C	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\pi^0)/\Gamma_{\text{total}}$ Γ_{35}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 54	95	[21] LIBERMAN	75	SPEC	e^+e^-
<100	90	WIIK	75	DASP	e^+e^-

$\Gamma(\gamma\eta'(958))/\Gamma_{\text{total}}$ Γ_{36}/Γ

VALUE (units 10^{-2})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.11	90	[22] BARTEL	76	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	[23] BRAUNSCH...	77	DASP	e^+e^-

$\Gamma(\gamma\eta)/\Gamma_{\text{total}}$ Γ_{37}/Γ

VALUE (units 10^{-2})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	90	YAMADA	77	DASP	$e^+e^- \rightarrow 3\gamma$

$\Gamma(\gamma\eta(1440) \rightarrow \gamma K\bar{K}\pi)/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.12	90	[24] SCHARRE	80	MRK1	e^+e^-

[17] Angular distribution $(1+\cos^2\theta)$ assumed.
[18] Angular distribution $(1-0.189\cos^2\theta)$ assumed.
[19] Valid for isotropic distribution of the photon.
[20] Angular distribution $(1-0.052\cos^2\theta)$ assumed.
[21] Restated by us using $B(\psi(2S) \rightarrow \mu^+\mu^-) = 0.0077$.
[22] The value is normalized to the branching ratio for $\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$.
[23] Restated by us using total decay width 228 keV.
[24] Includes unknown branching fraction $\eta(1440) \rightarrow K\bar{K}\pi$.

$\psi(2S)$ REFERENCES

ARMSTRONG	97	PR D55 1153	+Bettoni, Bharadwaj+	(E760 Collab.)
GRIBUSHIN	96	PR D53 4723	+Abramov, Antipov+	(E672 Collab., E706 Collab.)
ANTONIAZZI	94	PR D50 4258	+Arenton+	(E705 Collab.)
ARMSTRONG	93B	PR D47 772	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
OREGLIA	80	PRL 45 959	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
BRAUNSCH...	77	PL 67B 249	Braunschweig+	(DASP Collab.)
BURMESTER	77	PL 66B 395	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DASP Collab.)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEIDP)
TANENBAUM	76	PRL 36 402	+Abrams, Boyarski, Bulos+	(SLAC, LBL) IG
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)
ABRAMS	75	Stanford Symp. 25		(LBL)
ABRAMS	75B	PRL 34 1181	+Briggs, Chinowsky, Friedberg+	(LBL, SLAC)
BOYARSKI	75C	Palermo Conf. 54	+Breidenbach, Bulos, Abrams, Briggs+	(SLAC, LBL)
HILGER	75	PRL 35 625	+Beron, Ford, Hofstadter, Howell+	(STAN, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
LUTH	75	PRL 35 1124	+Boyarski, Lynch, Breidenbach+	(SLAC, LBL) JPC
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

HOU	97	PR D55 6952	Wei-Shu Hou	
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
AUBERT	75B	PRL 33 1624	+Becker, Biggs, Burger, Glenn+	(MIT, BNL)
BRAUNSCH...	75B	PL 57B 407	Braunschweig, Konigs+	(DASP Collab.)
CAMERINI	75	PRL 35 483	+Learned, Prepost, Ash, Anderson+	(WISC, SLAC)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
GRECO	75	PL 56B 367	+Pancheri-Srivastava, Srivastava	(FRAS)
JACKSON	75	NIM 128 13	+Scharre	(LBL)
SIMPSON	75	PRL 35 699	+Beron, Ford, Hilger, Hofstadter+	(STAN, PENN)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

ψ(3770) MASS

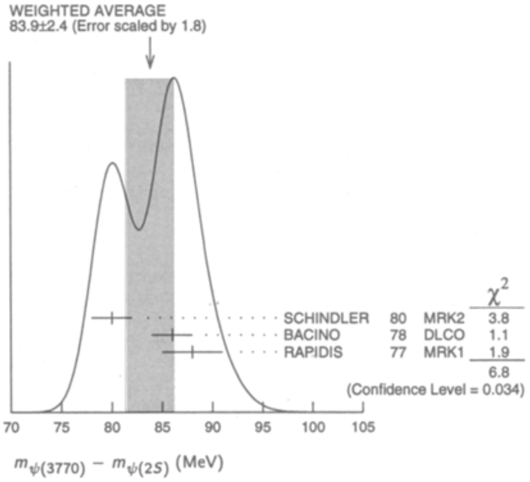
VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3769.9±2.5 OUR EVALUATION	Error includes scale factor of 1.8. From $m_{\psi(2S)}$ and mass difference below.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3764 ±5	[1] SCHINDLER 80	MRK2	e^+e^-
3770 ±6	[1] BACINO 78	DLCO	e^+e^-
3772 ±6	[1] RAPIDIS 77	MRK1	e^+e^-

[1] Errors include systematic common to all experiments.

$m_{\psi(3770)} - m_{\psi(2S)}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
83.9±2.4 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.		
80 ±2	SCHINDLER 80	MRK2	e^+e^-
86 ±2	[2] BACINO 78	DLCO	e^+e^-
88 ±3	RAPIDIS 77	MRK1	e^+e^-

[2] SPEAR $\psi(2S)$ mass subtracted (see SCHINDLER 80).



ψ(3770) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
23.6±2.7 OUR FIT	Error includes scale factor of 1.1.		
25.3±2.9 OUR AVERAGE			
24 ±5	SCHINDLER 80	MRK2	e^+e^-
24 ±5	BACINO 78	DLCO	e^+e^-
28 ±5	RAPIDIS 77	MRK1	e^+e^-

ψ(3770) DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$D\overline{D}$	dominant	
Γ_2	e^+e^-	$(1.12\pm0.17) \times 10^{-5}$	1.2

ψ(3770) PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.26 ±0.04 OUR FIT	Error includes scale factor of 1.2.		
0.24 ±0.05 OUR AVERAGE	Error includes scale factor of 1.2.		
0.276±0.050	SCHINDLER 80	MRK2	e^+e^-
0.18 ±0.06	BACINO 78	DLCO	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.37 ±0.09	[3] RAPIDIS 77	MRK1	e^+e^-

[3] See also $\Gamma(e^+e^-)/\Gamma_{\text{total}}$ below.

ψ(3770) BRANCHING RATIOS

$\Gamma(D\overline{D})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	PERUZZI 77	MRK1	$e^+e^- \to D\overline{D}$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
1.12±0.17 OUR FIT	Error includes scale factor of 1.2.		
1.3 ±0.2	RAPIDIS 77	MRK1	e^+e^-

ψ(3770) REFERENCES

SCHINDLER	80	PR D21 2716	+Siegrist, Alam, Boyarski+	(Mark II Collab.)
BACINO	78	PRL 40 671	+Baumgarten, Birkwood+	(SLAC, UCLA, UCI)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(Mark I Collab.)
RAPIDIS	77	PRL 39 526	+Gobbi, Luke, Barbaro-Galtieri+	(Mark I Collab.)

$\psi(4040)$

$I^G(J^{PC}) = ?^?(1^{--})$

ψ(4040) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4040±10	BRANDELIK 78C	DASP	e^+e^-

ψ(4040) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
52±10	BRANDELIK 78C	DASP	e^+e^-

ψ(4040) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.4\pm0.4) \times 10^{-5}$
Γ_2	$D^0\overline{D}^0$	seen
Γ_3	$D^*(2007)^0\overline{D}^0$ + c.c.	seen
Γ_4	$D^*(2007)^0\overline{D}^*(2007)^0$	seen
Γ_5	$J/\psi(1S)$ hadrons	
Γ_6	$\mu^+\mu^-$	

ψ(4040) PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.75±0.15	BRANDELIK 78C	DASP	e^+e^-

ψ(4040) BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 1.0	FELDMAN 77	MRK1	e^+e^-

$\Gamma(D^0\overline{D}^0)/\Gamma(D^*(2007)^0\overline{D}^0$+c.c.) Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 ±0.03	[1] GOLDHABER 77	MRK1	e^+e^-

$\Gamma(D^*(2007)^0\overline{D}^*(2007)^0)/\Gamma(D^*(2007)^0\overline{D}^0$+c.c.) Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
32.0±12.0	[1] GOLDHABER 77	MRK1	e^+e^-

[1] Phase-space factor (p^3) explicitly removed.

ψ(4040) REFERENCES

BRANDELIK	78C	PL 76B 361	+Cords+	(DASP Collab.)
Also	79C	ZPHY C1 233	Brandelik, Cords+	(DASP Collab.)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)

OTHER RELATED PAPERS

HEIKKILA	84	PR D29 110	+Tornqvist, Ono	(HELS, AACHT)
ONO	84	ZPHY C26 307		(ORSAY)
SIEGRIST	82	PR D26 969	+Schwitters, Alam, Chinowsky+	(SLAC, LBL)
AUGUSTIN	75	PRL 34 764	+Boyarski, Abrams, Briggs+	(SLAC, LBL)
BACCI	75	PL 58B 481	+Bidoli, Penso, Stella+	(ROMA, FRAS)
BOYARSKI	75B	PRL 34 762	+Breidenbach, Abrams, Briggs+	(SLAC, LBL)
ESPOSITO	75	PL 58B 478	+Felicetti, Peruzzi+	(FRAS, NAPL, PADO, ROMA)

$\psi(4160)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(4160)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
4159±20	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
78±20	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(10\pm4)\times10^{-6}$

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ **Γ_1**

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.77±0.23	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)

OTHER RELATED PAPERS

ONO 84 ZPHY C26 307 (ORSAY)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)

$\psi(4415)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(4415)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
4415± 6 OUR AVERAGE			
4417±10	BRANDELIK 78C	DASP	e^+e^-
4414± 7	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
43±15 OUR AVERAGE	Error includes scale factor of 1.8.		
66±15	BRANDELIK 78C	DASP	e^+e^-
33±10	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	dominant
Γ_2	e^+e^-	$(1.1\pm0.4)\times10^{-5}$

$\psi(4415)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ **Γ_2**

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.47±0.10 OUR AVERAGE			
0.49±0.13	BRANDELIK 78C	DASP	e^+e^-
0.44±0.14	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
dominant	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)
SIEGRIST 76 PRL 36 700 +Abrams, Boyarski, Breidenbach+ (LBL, SLAC)

OTHER RELATED PAPERS

BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
LUTH 77 PL 70B 120 +Pierre, Abrams, Alam, Boyarski+ (LBL, SLAC)

$b\bar{b}$ MESONS

WIDTH DETERMINATIONS OF THE Υ STATES

As is the case for the $J/\psi(1S)$ and $\psi(2S)$, the full widths of the $b\bar{b}$ states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ are not directly measurable, since they are much narrower than the energy resolution of the e^+e^- storage rings where these states are produced. The common indirect method to determine Γ starts from

$$\Gamma = \Gamma_{\ell\ell}/B_{\ell\ell} \; , \qquad (1)$$

where $\Gamma_{\ell\ell}$ is one leptonic partial width and $B_{\ell\ell}$ is the corresponding branching fraction ($\ell = e$, μ, or τ). One then assumes e-μ-τ universality and uses

$$\Gamma_{\ell\ell} = \Gamma_{ee}$$

$$B_{\ell\ell} = \text{average of } B_{ee},\ B_{\mu\mu}, \text{ and } B_{\tau\tau} \; . \qquad (2)$$

The electronic partial width Γ_{ee} is also not directly measurable at e^+e^- storage rings, only in the combination $\Gamma_{ee}\Gamma_{\text{had}}/\Gamma$, where Γ_{had} is the hadronic partial width and

$$\Gamma_{\text{had}} + 3\Gamma_{ee} = \Gamma \; . \qquad (3)$$

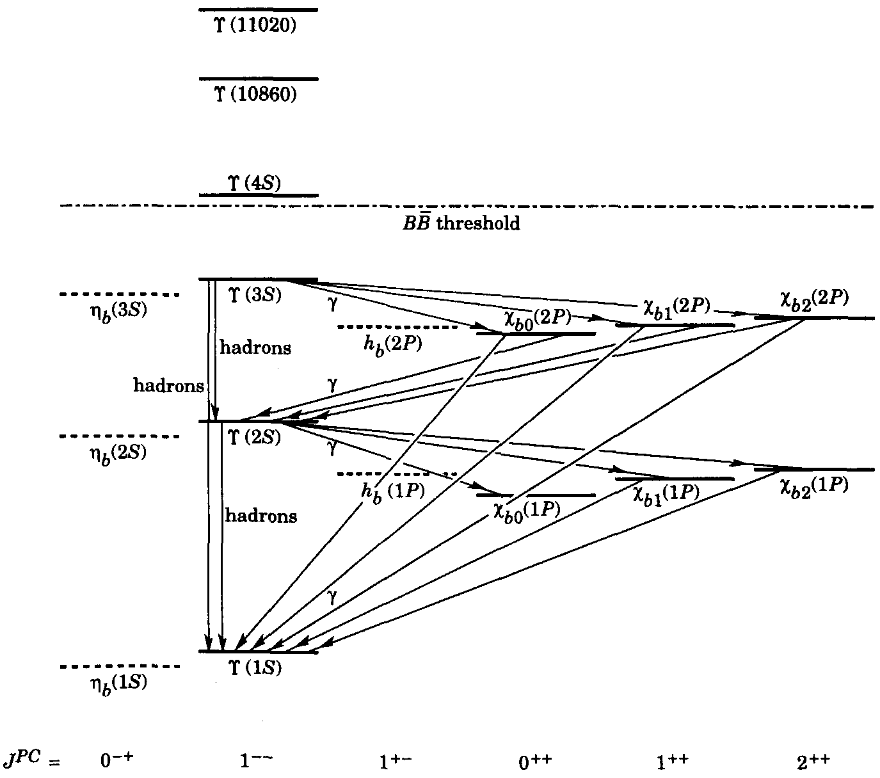
This combination is obtained experimentally from the energy-integrated hadronic cross section

$$\int_{\text{resonance}} \sigma(e^+e^- \to \Upsilon \to \text{hadrons})dE$$

$$= \frac{6\pi^2}{M^2}\frac{\Gamma_{ee}\Gamma_{\text{had}}}{\Gamma}C_r = \frac{6\pi^2}{M^2}\frac{\Gamma^{(0)}_{ee}\Gamma_{\text{had}}}{\Gamma}C_r^{(0)} \; , \qquad (4)$$

where M is the Υ mass, and C_r and $C_r^{(0)}$ are radiative correction factors. C_r is used for obtaining Γ_{ee} as defined in Eq. (1), and contains corrections from all orders of QED for describing $(b\bar{b}) \to e^+e^-$. The lowest order QED value $\Gamma^{(0)}_{ee}$, relevant for comparison with potential-model calculations, is defined by the lowest order QED graph (Born term) alone, and is about 7% lower than Γ_{ee}.

THE BOTTOMONIUM SYSTEM



The level scheme of the $b\bar{b}$ states showing experimentally established states with solid lines. Singlet states are called η_b and h_b, triplet states Υ and χ_{bJ}. In parentheses it is sufficient to give the radial quantum number and the orbital angular momentum to specify the states with all their quantum numbers. *E.g.*, $h_b(2P)$ means 2^1P_1 with $n = 2$, $L = 1$, $S = 0$, $J = 1$, $PC = +-$. If found, D-wave states would be called $\eta_b(nD)$ and $\Upsilon_J(nD)$, with $J = 1,2,3$ and $n = 1,2,3,4,\cdots$. For the χ_b states, the spins of only the $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$ have been experimentally established. The spins of the other χ_b are given as the preferred values, based on the quarkonium models. The figure also shows the observed hadronic and radiative transitions.

The Listings give experimental results on B_{ee}, $B_{\mu\mu}$, $B_{\tau\tau}$, and $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$. The entries of the last quantity have been re-evaluated consistently using the correction procedure of KURAEV 85.The partial width Γ_{ee} is obtained from the average values for $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$ and $B_{\ell\ell}$ using

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma(1-3B_{\ell\ell})} \,. \tag{5}$$

The total width Γ is then obtained from Eq. (1). We do not list Γ_{ee} and Γ values of individual experiments. The Γ_{ee} values in the Meson Summary Table are also those defined in Eq. (1).

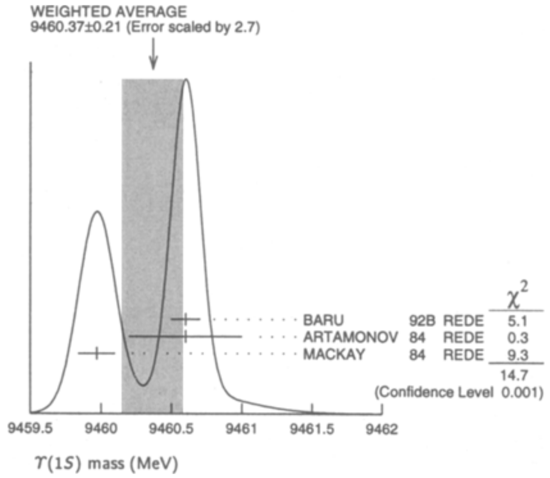
$\boxed{\Upsilon(1S)}$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(1S)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9460.37±0.21 OUR AVERAGE	Error includes scale factor of 2.7. See the ideogram below.			
9460.60±0.09±0.05	[1] BARU	92B	REDE	$e^+e^- \to$ hadrons
9460.6 ±0.4	[2] ARTAMONOV	84	REDE	$e^+e^- \to$ hadrons
9459.97±0.11±0.07	MACKAY	84	REDE	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9460.59±0.12	BARU	86	REDE	$e^+e^- \to$ hadrons

[1] Superseding BARU 86.
[2] Value includes data of ARTAMONOV 82.



$\Upsilon(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID
52.5±1.8 OUR EVALUATION	See the Note on Width Determinations of the Υ states

$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\tau^+\tau^-$	$(2.67^{+0.14}_{-0.16})$ %	
Γ_2	e^+e^-	(2.52 ± 0.17) %	
Γ_3	$\mu^+\mu^-$	(2.48 ± 0.07) %	S=1.1
	Hadronic decays		
Γ_4	$J/\psi(1S)$anything	$(1.1\pm0.4)\times10^{-3}$	
Γ_5	$\rho\pi$	$<2\times10^{-4}$	CL=90%
Γ_6	$\pi^+\pi^-$	$<5\times10^{-4}$	CL=90%
Γ_7	K^+K^-	$<5\times10^{-4}$	CL=90%
Γ_8	$p\overline{p}$	$<5\times10^{-4}$	CL=90%
Γ_9	$D^*(2010)^\pm$anything		
	Radiative decays		
Γ_{10}	$\gamma 2h^+2h^-$	$(7.0\pm1.5)\times10^{-4}$	
Γ_{11}	$\gamma 3h^+3h^-$	$(5.4\pm2.0)\times10^{-4}$	
Γ_{12}	$\gamma 4h^+4h^-$	$(7.4\pm3.5)\times10^{-4}$	
Γ_{13}	$\gamma\pi^+\pi^-K^+K^-$	$(2.9\pm0.9)\times10^{-4}$	
Γ_{14}	$\gamma 2\pi^+2\pi^-$	$(2.5\pm0.9)\times10^{-4}$	
Γ_{15}	$\gamma 3\pi^+3\pi^-$	$(2.5\pm1.2)\times10^{-4}$	
Γ_{16}	$\gamma 2\pi^+2\pi^-K^+K^-$	$(2.4\pm1.2)\times10^{-4}$	
Γ_{17}	$\gamma\pi^+\pi^-p\overline{p}$	$(1.5\pm0.6)\times10^{-4}$	
Γ_{18}	$\gamma 2\pi^+2\pi^-p\overline{p}$	$(4\pm6)\times10^{-5}$	
Γ_{19}	$\gamma 2K^+2K^-$	$(2.0\pm2.0)\times10^{-5}$	
Γ_{20}	$\gamma\eta'(958)$	$<1.3\times10^{-3}$	CL=90%
Γ_{21}	$\gamma\eta$	$<3.5\times10^{-4}$	CL=90%
Γ_{22}	$\gamma f'_2(1525)$	$<1.4\times10^{-4}$	CL=90%
Γ_{23}	$\gamma f_2(1270)$	$<1.3\times10^{-4}$	CL=90%
Γ_{24}	$\gamma\eta(1440)$	$<8.2\times10^{-5}$	CL=90%
Γ_{25}	$\gamma f_J(1710)\to\gamma K\overline{K}$	$<2.6\times10^{-4}$	CL=90%
Γ_{26}	$\gamma f_0(2200)\to\gamma K^+K^-$	$<2\times10^{-4}$	CL=90%
Γ_{27}	$\gamma f_J(2220)\to\gamma K^+K^-$	$<1.5\times10^{-5}$	CL=90%
Γ_{28}	$\gamma\eta(2225)\to\gamma\phi\phi$	$<3\times10^{-3}$	CL=90%
Γ_{29}	γX X = pseudoscalar with $m<7.2$ GeV)	$<3\times10^{-5}$	CL=90%
Γ_{30}	$\gamma X\overline{X}$ $X\overline{X}$ = vectors with $m<3.1$ GeV)	$<1\times10^{-3}$	CL=90%

$\Upsilon(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-)\times\Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ — $\Gamma_2\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
31.2±1.6±1.7	KOBEL	92	CBAL	$e^+e^-\to\mu^+\mu^-$

$\Gamma(\text{hadrons})\times\Gamma(e^+e^-)/\Gamma_{\rm total}$ — $\Gamma_0\Gamma_2/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
1.216±0.027 OUR AVERAGE				
1.187±0.023±0.031	[3] BARU	92B	MD1	$e^+e^-\to$ hadrons
1.23 ±0.02 ±0.05	[3] JAKUBOWSKI	88	CBAL	$e^+e^-\to$ hadrons
1.37 ±0.06 ±0.09	[4] GILES	84B	CLEO	$e^+e^-\to$ hadrons
1.23 ±0.08 ±0.04	[4] ALBRECHT	82	DASP	$e^+e^-\to$ hadrons
1.13 ±0.07 ±0.11	[4] NICZYPORUK	82	LENA	$e^+e^-\to$ hadrons
1.09 ±0.25	[4] BOCK	80	CNTR	$e^+e^-\to$ hadrons
1.35 ±0.14	[5] BERGER	79	PLUT	$e^+e^-\to$ hadrons

[3] Radiative corrections evaluated following KURAEV 85.
[4] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.
[5] Radiative corrections reevaluated by ALEXANDER 89 using $B(\mu\mu) = 0.026$.

$\Upsilon(1S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
1.32±0.04±0.03	[6] ALBRECHT	95E	ARG	$e^+e^-\to$ hadrons

[6] Applying the formula of Kuraev and Fadin.

$\Upsilon(1S)$ BRANCHING RATIOS

$\Gamma(\tau^+\tau^-)/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.0267^{+0.0014}_{-0.0016}$ OUR AVERAGE					
$0.0261\pm0.0012^{+0.0009}_{-0.0013}$	25k	CINABRO	94B	CLE2	$e^+e^-\to\tau^+\tau^-$
0.027 ±0.004 ±0.002		[7] ALBRECHT	85C	ARG	$\Upsilon(2S)\to\pi^+\pi^-\tau^+\tau^-$
0.034 ±0.004 ±0.004		GILES	83	CLEO	$e^+e^-\to\tau^+\tau^-$

[7] Using $B(\Upsilon(1S)\to ee) = B(\Upsilon(1S)\to\mu\mu) = 0.0256$; not used for width evaluations.

$\Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0248±0.0007 OUR AVERAGE	Error includes scale factor of 1.1.				
0.0212±0.0020±0.0010		[8] BARU	92	MD1	$e^+e^-\to\mu^+\mu^-$
0.0231±0.0012±0.0010		[8] KOBEL	92	CBAL	$e^+e^-\to\mu^+\mu^-$
0.0252±0.0007±0.0007		CHEN	89B	CLEO	$e^+e^-\to\mu^+\mu^-$
0.0261±0.0009±0.0011		KAARSBERG	89	CSB2	$e^+e^-\to\mu^+\mu^-$
0.0230±0.0025±0.0013	86	ALBRECHT	87	ARG	$\Upsilon(2S)\to\pi^+\pi^-\mu^+\mu^-$
0.029 ±0.003 ±0.002	864	BESSON	84	CLEO	$\Upsilon(2S)\to\pi^+\pi^-\mu^+\mu^-$

0.027 ±0.003 ±0.003		ANDREWS 83	CLEO	$e^+e^- \to \mu^+\mu^-$
0.032 ±0.013 ±0.003		ALBRECHT 82	DASP	$e^+e^- \to \mu^+\mu^-$
0.038 ±0.015 ±0.002		NICZYPORUK 82	LENA	$e^+e^- \to \mu^+\mu^-$
$0.014 {}^{+0.034}_{-0.014}$		BOCK 80	CNTR	$e^+e^- \to \mu^+\mu^-$
0.022 ±0.020		BERGER 79	PLUT	$e^+e^- \to \mu^+\mu^-$

[8] Taking into account interference between the resonance and continuum.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0252±0.0017 OUR AVERAGE				
0.0242±0.0014±0.0014	307	ALBRECHT 87	ARG	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.028 ±0.003 ±0.002	826	BESSON 84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.051 ±0.030		BERGER 80C	PLUT	$e^+e^- \to e^+e^-$

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 0.68	90	ALBRECHT 92J	ARG	$e^+e^- \to e^+e^-X$, $e^+e^- \to \mu^+\mu^-X$
1.1 ±0.4±0.2		[9] FULTON 89	CLEO	$e^+e^- \to \mu^+\mu^-X$

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 1.7	90	MASCHMANN 90	CBAL	$e^+e^- \to$ hadrons
<20	90	NICZYPORUK 83	LENA	

[9] Using $B((J/\psi) \to \mu^+\mu^-) = (6.9 \pm 0.9)\%$.

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<5	90	BARU 92	MD1	$\Upsilon(1S) \to \pi^+\pi^-$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<5	90	BARU 92	MD1	$\Upsilon(1S) \to K^+K^-$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<5	90	[10] BARU 96	MD1	$\Upsilon(1S) \to p\overline{p}$

[10] Supersedes BARU 92 in this node.

$\Gamma(\gamma X)/\Gamma_{\text{total}}$ Γ_{29}/Γ

(X = pseudoscalar with $m <$ 7.2 GeV)

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3	90	[11] BALEST 95	CLEO	$e^+e^- \to \gamma + X$

[11] For a noninteracting pseudoscalar X with mass < 7.2 GeV.

$\Gamma(\gamma X\overline{X})/\Gamma_{\text{total}}$ Γ_{30}/Γ

($X\overline{X}$ = vectors with $m <$ 3.1 GeV)

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1	90	[12] BALEST 95	CLEO	$e^+e^- \to \gamma + X\overline{X}$

[12] For a noninteracting vector X with mass < 3.1 GeV.

$\Gamma(\gamma 2\pi^+2\pi^-)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.5±0.7±0.5	26 ± 7	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.9±0.7±0.6	29 ± 8	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.5±0.5±0.3	22 ± 6	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2K^+2K^-)/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.2 ±0.2	2 ± 2	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3\pi^+3\pi^-)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.5±0.9±0.8	17 ± 5	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+2\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.4±0.9±0.8	18 ± 7	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+2\pi^-p\overline{p})/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.4±0.4±0.4	7 ± 6	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2h^+2h^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
7.0±1.1±1.0	80 ± 12	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3h^+3h^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5.4±1.5±1.3	39 ± 11	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 4h^+4h^-)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
7.4±2.5±2.5	36 ± 12	FULTON 90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 2	90	FULTON 90B		$\Upsilon(1S) \to \rho^0\pi^0$

• • • We do not use the following data for averages, fits, limits, etc. • • •

<10	90	BLINOV 90	MD1	$\Upsilon(1S) \to \rho^0\pi^0$
<21	90	NICZYPORUK 83	LENA	$\Upsilon(1S) \to \rho^0\pi^0$

$\Gamma(D^*(2010)^{\pm}\text{anything})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<19	90	[13] ALBRECHT 92J	ARG	$e^+e^- \to D^0\pi^{\pm}X$

[13] For $x_p > 0.2$.

$\Gamma(\gamma\eta(1440))/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<8.2	90	[14] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^+\pi^{\mp}K^0_S$

[14] Includes unknown branching ratio of $\eta(1440) \to K^{\pm}\pi^{\mp}K^0_S$.

$\Gamma(\gamma\eta'(958))/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.3	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma\eta)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3.5	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma f'_2(1525))/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<14	90	[15] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

<19.4	90	[15] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$

[15] Assuming $B(f'_2(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_J(1710) \to \gamma K\overline{K})/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 2.6	90	[16] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 6.3	90	[16] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
<19	90	[16] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^0_S K^0_S$
< 8	90	[17] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<24	90	[18] SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

[16] Assuming $B(f_J(1710) \to K\overline{K}) = 0.38$.

[17] Assuming $B(f_J(1710) \to \pi\pi) = 0.04$.

[18] Assuming $B(f_J(1710) \to \eta\eta) = 0.18$.

$\Gamma(\gamma f_2(1270))/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<13	90	[19] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

<21	90	[19] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<81	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

[19] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_J(2220) \to \gamma K^+K^-)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 1.5	90	[20] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 2.9	90	[20] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
<20	90	[20] BARU 89	MD1	$\Upsilon(1S) \to \gamma K^+K^-$

[20] Including unknown branching ratio of $f_J(2220) \to K^+K^-$.

$\Gamma(\gamma\eta(2225) \to \gamma\phi\phi)/\Gamma_{\rm total}$ Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	[21] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+ K^- K^+ K^-$

[21] Assuming that the $\eta(2225)$ decays only into $\phi\phi$.

$\Gamma(\gamma f_0(2200) \to \gamma K^+ K^-)/\Gamma_{\rm total}$ Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0002	90	[22] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+ K^-$

[22] Assuming that the $f_0(2200)$ decays only into $K^+ K^-$.

$\Upsilon(1S)$ REFERENCES

BARU	96	PRPL 267 71	+Blinov, Blinov, Bondar+	(NOVO)
ALBRECHT	95E	ZPHY C65 619	+Hamacher+	(ARGUS Collab.)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
CINABRO	94B	PL B340 129	+Liu, Saulnier, Wilson+	(CLEO Collab.)
ALBRECHT	92J	ZPHY C55 25	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BARU	92	ZPHY C54 229	+Beilin, Blinov+	(NOVO)
BARU	92B	ZPHY C56 547	+Blinov, Blinov, Bondar+	(NOVO)
KOBEL	92	ZPHY C53 193	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
BLINOV	90	PL B245 311	+Bondar+	(NOVO)
FULTON	90B	PR D41 1401	+Hempstead+	(CLEO Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
BARU	89	ZPHY C42 505	+Beilin, Blinov, Blinov+	(NOVO)
CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
FULTON	89	PL B224 445	+Haas, Hempstead+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, DESY, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
SCHMITT	88	ZPHY C40 199	+Antreasyan+	(Crystal Ball Collab.)
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
BARU	86	ZPHY C30 551	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85C	PL 154B 452	+Drescher, Heller+	(ARGUS Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(NOVO)
		Translated from YAF 41 733.		
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
MACKAY	84	PR D29 2483	+Hasard, Giles, Hempstead+	(CUSB Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GILES	83	PRL 50 877	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+	(LENA Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEIDH, LUND, ITEP)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
NICZYPORUK	82	ZPHY C15 299	+Folger, Bienlein+	(LENA Collab.)
BERGER	80C	PL 93B 497	+Lackas, Raupach+	(PLUTO Collab.)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEIDP, MPIM, DESY, HAMB)
BERGER	79	ZPHY C1 343	+Alexander+	(PLUTO Collab.)

OTHER RELATED PAPERS

KOENIGS...	86	DESY 86/136	Koenigsmann	(DESY)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
BERGER	78	PL 76B 243	+Alexander, Daum+	(PLUTO Collab.)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEIDP, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEIDH, LUND)
GARELICK	78	PR D18 945	+Gauthier, Hicks, Oliver+	(NEAS, WASH, TUFTS)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\chi_{b0}(1P)$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9859.8±1.3 OUR AVERAGE				
9860.0±0.5±1.4	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
9858.3±1.6±2.7	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9864.1±7 ±1	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9872.8±0.7±5.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
162.3±1.3 OUR AVERAGE				
162.1±0.5±1.4	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
163.8±1.6±2.7	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
158.0±7 ±1	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149.4±0.7±5.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

$\chi_{b0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\gamma\Upsilon(1S)$	<6 %	90%

$\chi_{b0}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.06	90	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	90	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b0}(1P)$ REFERENCES

WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 1$ from SKWARNICKI 87.

$\chi_{b1}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9891.9±0.7 OUR AVERAGE				
9890.8±0.9±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
9890.8±0.3±1.1	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
9892.0±0.8±2.4	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9893.6±0.8±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
9894.4±0.4±3.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
9892 ±3	[1] PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130.6±0.7 OUR AVERAGE				
131.7±0.9±1.3	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
131.7±0.3±1.1	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
130.6±0.8±2.4	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
129 ±0.8±1	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
128.1±0.4±3.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
130.6±3.0	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(35±8) %

$\chi_{b1}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35±0.08 OUR AVERAGE				
0.32±0.06±0.07	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
0.47±0.18	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.) J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 2$ from SKWARNICKI 87.

$\chi_{b2}(1P)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9913.2±0.6 OUR AVERAGE				
9915.8±1.1±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
9912.2±0.3±0.9	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv.γX
9912.4±0.8±2.2	[1] NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
9913.3±0.7±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv.γX
9914.6±0.3±2.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
9914 ±4	[1] PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
109.6±0.6 OUR AVERAGE				
107.0±1.1±1.3	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
110.6±0.3±0.9	ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv.γX
110.4±0.8±2.2	NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
109.5±0.7±1.0	HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv.γX
108.2±0.3±2.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
108.8±4.0	PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(22±4) %

$\chi_{b2}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.22±0.04 OUR AVERAGE				
0.27±0.06±0.06	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
0.20±0.05	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.) J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(2S)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.02330±0.00031 OUR AVERAGE				
10.0236 ±0.0005	[1] BARU	86B	REDE	$e^+e^- \rightarrow$ hadrons
10.0231 ±0.0004	BARBER	84	REDE	$e^+e^- \rightarrow$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(2S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
44±7 OUR EVALUATION	See the Note on Width Determinations of the Υ states

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(18.5 ±0.8) %	
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(8.8 ±1.1) %	
Γ_3	$\tau^+\tau^-$	(1.7 ±1.6) %	
Γ_4	$\mu^+\mu^-$	(1.31±0.21) %	
Γ_5	e^+e^-	(1.18±0.20) %	
Γ_6	$\Upsilon(1S)\pi^0$	< 8 × 10^{-3}	90%
Γ_7	$\Upsilon(1S)\eta$	< 2 × 10^{-3}	90%
Γ_8	$J/\psi(1S)$anything	< 6 × 10^{-3}	90%
	Radiative decays		
Γ_9	$\gamma\chi_{b1}(1P)$	(6.7 ±0.9) %	
Γ_{10}	$\gamma\chi_{b2}(1P)$	(6.6 ±0.9) %	
Γ_{11}	$\gamma\chi_{b0}(1P)$	(4.3 ±1.0) %	
Γ_{12}	$\gamma f_J(1710)$	< 5.9 × 10^{-4}	90%
Γ_{13}	$\gamma f'_2(1525)$	< 5.3 × 10^{-4}	90%
Γ_{14}	$\gamma f_2(1270)$	< 2.41 × 10^{-4}	90%
Γ_{15}	$\gamma f_J(2220)$		

$\Upsilon(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-) \times \Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_4/\Gamma$

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
6.5±1.5±1.0	KOBEL	92	CBAL	$e^+e^- \rightarrow \mu^+\mu^-$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_0\Gamma_5/\Gamma$

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.553±0.023 OUR AVERAGE				
0.552±0.031±0.017	[2] BARU	96	MD1	$e^+e^- \rightarrow$ hadrons
0.54 ±0.04 ±0.02	[2] JAKUBOWSKI	88	CBAL	$e^+e^- \rightarrow$ hadrons
0.58 ±0.03 ±0.04	[3] GILES	84B	CLEO	$e^+e^- \rightarrow$ hadrons
0.60 ±0.12 ±0.07	[3] ALBRECHT	82	DASP	$e^+e^- \rightarrow$ hadrons
0.54 ±0.07 $^{+0.09}_{-0.05}$	[3] NICZYPORUK	81C	LENA	$e^+e^- \rightarrow$ hadrons
0.41 ±0.18	[3] BOCK	80	CNTR	$e^+e^- \rightarrow$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.

[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(2S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_5

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.52 ±0.03 ±0.01	[4] ALBRECHT	95E	ARG	$e^+e^- \rightarrow$ hadrons

[4] Applying the formula of Kuraev and Fadin.

$\Upsilon(2S)$ BRANCHING RATIOS

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.006	90	MASCHMANN	90	CBAL	$e^+e^- \rightarrow$ hadrons

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.185±0.008 OUR AVERAGE					
0.181±0.005±0.010	11.6k	ALBRECHT	87	ARG	$e^+e^- \rightarrow \pi^+\pi^-$ MM
0.169±0.040		GELPHMAN	85	CBAL	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
0.191±0.012±0.006		BESSON	84	CLEO	$\pi^+\pi^-$ MM
0.189±0.026		FONSECA	84	CUSB	$e^+e^- \rightarrow \ell^+\ell^-\pi^+\pi^-$
0.21 ±0.07	7	NICZYPORUK	81B	LENA	$e^+e^- \rightarrow \ell^+\ell^-\pi^+\pi^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.088±0.011 OUR AVERAGE					
0.095±0.019±0.019	25	ALBRECHT	87	ARG	$e^+e^- \rightarrow \pi^0\pi^0\ell^+\ell^-$
0.080±0.015		GELPHMAN	85	CBAL	$e^+e^- \rightarrow \ell^+\ell^-\pi^0\pi^0$
0.103±0.023		FONSECA	84	CUSB	$e^+e^- \rightarrow \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\tau^+\tau^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.017±0.015±0.006	HAAS	84B	CLEO	$e^+e^- \rightarrow \tau^+\tau^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.0131±0.0021 OUR AVERAGE					
0.0122±0.0028±0.0019		[5] KOBEL	92	CBAL	$e^+e^- \rightarrow \mu^+\mu^-$
0.0138±0.0025±0.0015		KAARSBERG	89	CSB2	$e^+e^- \rightarrow \mu^+\mu^-$
0.009 ±0.006 ±0.006		[6] ALBRECHT	85	ARG	$e^+e^- \rightarrow \mu^+\mu^-$
0.018 ±0.008 ±0.005		HAAS	84B	CLEO	$e^+e^- \rightarrow \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.038	90	NICZYPORUK	81C	LENA	$e^+e^- \rightarrow \mu^+\mu^-$

[5] Taking into account interference between the resonance and continuum.

[6] Re-evaluated using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 0.026$.

$\Gamma(\Upsilon(1S)\pi^0)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.008	90	LURZ	87	CBAL	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	FONSECA	84	CUSB	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.005	90	ALBRECHT	87	ARG	$e^+e^- \to \pi^+\pi^-\ell^+\ell^-$ MM
<0.007	90	LURZ	87	CBAL	$e^+e^- \to \ell^+\ell^-(\gamma\gamma, 3\pi^0)$
<0.010	90	BESSON	84	CLEO	

$\Gamma(\gamma\chi_{b1}(1P))/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.067±0.009 OUR AVERAGE				
0.091±0.018±0.022	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.065±0.007±0.012	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.080±0.017±0.016	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
0.059±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b2}(1P))/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.066±0.009 OUR AVERAGE				
0.098±0.021±0.024	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.058±0.007±0.010	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.102±0.018±0.021	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
0.061±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(1P))/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.043±0.010 OUR AVERAGE				
0.064±0.014±0.016	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.036±0.008±0.009	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.044±0.023±0.009	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma f_J(1710))/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<59	90	[7] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.9	90	[8] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[7] Re-evaluated assuming $B(f_J(1710) \to K^+K^-) = 0.19$.

[8] Includes unknown branching ratio of $f_J(1710) \to \pi^+\pi^-$.

$\Gamma(\gamma f'_2(1525))/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<53	90	[9] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[9] Re-evaluated assuming $B(f'_2(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_2(1270))/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<24.1	90	[10] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[10] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_J(2220))/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.8	90	[11] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[11] Includes unknown branching ratio of $f_J(2220) \to K^+K^-$.

$\Upsilon(2S)$ REFERENCES

BARU	96	PRPL 267 71	+Blinov, Blinov, Bondar+	(NOVO)
ALBRECHT	95E	ZPHY C65 619	+Hamacher+	(ARGUS Collab.)
KOBEL	92	ZPHY C53 193	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, DESY, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
LURZ	87	ZPHY C36 383	+Antreasyan, Besset+	(Crystal Ball Collab.)
BARU	86B	ZPHY C32 622	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85	ZPHY C28 45	+Dreschell, Heller+	(ARGUS Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
GELPHMAN	85	PR D11 2893	+Lurz, Antreasyan+	(Crystal Ball Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(NOVO)
		Translated from YAF 41 733.		
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BARBER	84	PL 135B 498	+	(DESY, ARGUS Collab., Crystal Ball Collab.)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
FONSECA	84	NP B242 31	+Mageras, Son, Dietl, Eigen+	(CUSB Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
HAAS	84B	PR D30 1996	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEIDH, LUND, ITEP)
NICZYPORUK	81B	PL 100B 95	+Chen, Folger, Lurz+	(LENA Collab.)
NICZYPORUK	81C	PL 99B 169	+Chen, Vogel, Wegener+	(LENA Collab.)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEIDP, MPIM, DESY, HAMB)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEIDP, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEIDH, LUND)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\boxed{\chi_{b0}(2P)}$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.2321±0.0006 OUR AVERAGE				
10.2312±0.0008±0.0012	[1] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$
10.2323±0.0007	[2] MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
122.8±0.5 OUR AVERAGE	Error includes scale factor of 1.1.				
123.0±0.8	4959	[3] HEINTZ	92	CSB2	$e^+e^- \to \gamma X$
124.6±1.4	17	[4] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
122.3±0.3±0.6	9903	MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[3] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b0}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(4.6±2.1) %
Γ_2	$\gamma\Upsilon(1S)$	(9 ±6) × 10^{-3}

$\chi_{b0}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.089	90	[5] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.046±0.020±0.007		[6] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[5] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.37 \pm 0.26)\%$, $B(\Upsilon(3S) \to \gamma\gamma\Upsilon(2S)) \times 2\, B(\Upsilon(2S) \to \mu^+\mu^-) < 1.19 \times 10^{-4}$, and $B(\Upsilon(3S) \to \chi_{b0}(2P)\gamma) = 0.049$.

[6] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.44 \pm 0.10)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = (6.0 \pm 0.4 \pm 0.6)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.025	90	[7] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.009±0.006±0.001		[8] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[7] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\gamma\Upsilon(1S)) \times 2\, B(\Upsilon(1S) \to \mu^+\mu^-) < 0.63 \times 10^{-4}$, and $B(\Upsilon(3S) \to \chi_{b0}(2P)\gamma) = 0.049$.

[8] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = (6.0 \pm 0.4 \pm 0.6)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b0}(2P)$ REFERENCES

CRAWFORD	92B	PL B294 139	+Fulton	(CLEO Collab.)
HEINTZ	92	PR D46 1928	+Lee, Franzini+	(CUSB II Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)

OTHER RELATED PAPERS

EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\chi_{b1}(2P)$

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b1}(2P)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.2552±0.0005 OUR AVERAGE				
10.2547±0.0004±0.0010	[1] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X, \ell^+\ell^-\gamma\gamma$
10.2553±0.0005	[2] MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final evaluation.

$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
23.5±0.7±0.7	[3] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X, \ell^+\ell^-\gamma\gamma$

[3] From the average photon energy for inclusive and exclusive events. Supersedes NARAIN 91.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
99.90±0.26 OUR AVERAGE					
99 ±1	169	CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
100.1 ±0.4	11147	[4] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X$
100.2 ±0.5	223	[5] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
99.5 ±0.1 ±0.5	25759	MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[5] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b1}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$\gamma\,\Upsilon(2S)$	(21 ±4) %	1.5
Γ_2	$\gamma\,\Upsilon(1S)$	(8.5±1.3) %	1.3

$\chi_{b1}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\,\Upsilon(2S))/\Gamma_{\text{total}}$ — **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.21 ±0.04 OUR AVERAGE	Error includes scale factor of 1.5.			
0.356±0.042±0.092	[6] CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
0.199±0.020±0.022	[7] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$

[6] Using $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.37 \pm 0.26)\%$, $B(\Upsilon(3S) \rightarrow \gamma\gamma\,\Upsilon(2S)) \times 2\,B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (10.23 \pm 1.20 \pm 1.26) \times 10^{-4}$, and $B(\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P)) = 0.105^{+0.003}_{-0.002} \pm 0.013$.

[7] Using $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.44 \pm 0.10)\%$, $B(\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P)) = (11.5 \pm 0.5 \pm 0.5)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\,\Upsilon(1S))/\Gamma_{\text{total}}$ — **Γ_2/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.085±0.013 OUR AVERAGE	Error includes scale factor of 1.3.			
0.120±0.021±0.021	[8] CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
0.080±0.009±0.007	[9] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$

[8] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \rightarrow \gamma\gamma\,\Upsilon(1S)) \times 2\,B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (6.47 \pm 1.12 \pm 0.82) \times 10^{-4}$ and $B(\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P)) = 0.105^{+0.003}_{-0.002} \pm 0.013$.

[9] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \rightarrow \gamma\chi_{b1}(2P)) = (11.5 \pm 0.5 \pm 0.5)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b1}(2P)$ REFERENCES

CRAWFORD 92B PL B294 139 +Fulton (CLEO Collab.)
HEINTZ 92 PR D46 1928 +Lee, Franzini+ (CUSB II Collab.)
HEINTZ 91 PRL 66 1563 +Kaarsberg+ (CUSB Collab.)
MORRISON 91 PRL 67 1696 +Schmidt+ (CLEO Collab.)
NARAIN 91 PRL 66 3113 +Lovelock+ (CUSB Collab.)

OTHER RELATED PAPERS

EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\chi_{b2}(2P)$

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b2}(2P)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.2685±0.0004 OUR AVERAGE				
10.2681±0.0004±0.0010	[1] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X, \ell^+\ell^-\gamma\gamma$
10.2685±0.0004	[2] MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below, assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
13.5±0.4±0.5	[3] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X, \ell^+\ell^-\gamma\gamma$

[3] From the average photon energy for inclusive and exclusive events. Supersedes NARAIN 91.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
86.64±0.23 OUR AVERAGE					
86 ±1	101	CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
86.7 ±0.4	10319	[4] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma X$
86.9 ±0.4	157	[5] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
86.4 ±0.1 ±0.4	30741	MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[5] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b2}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\,\Upsilon(2S)$	(16.2±2.4) %
Γ_2	$\gamma\,\Upsilon(1S)$	(7.1±1.0) %

$\chi_{b2}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\,\Upsilon(2S))/\Gamma_{\text{total}}$ — **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.162±0.024 OUR AVERAGE				
0.135±0.025±0.035	[6] CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
0.173±0.021±0.019	[7] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$

[6] Using $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.37 \pm 0.26)\%$, $B(\Upsilon(3S) \rightarrow \gamma\gamma\,\Upsilon(2S)) \times 2\,B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (4.98 \pm 0.94 \pm 0.62) \times 10^{-4}$, and $B(\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P)) = 0.135 \pm 0.003 \pm 0.017$.

[7] Using $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.44 \pm 0.10)\%$, $B(\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P)) = (11.1 \pm 0.5 \pm 0.4)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\,\Upsilon(1S))/\Gamma_{\text{total}}$ — **Γ_2/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.071±0.010 OUR AVERAGE				
0.072±0.014±0.013	[8] CRAWFORD	92B	CLE2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$
0.070±0.010±0.006	[9] HEINTZ	92	CSB2	$e^+e^- \rightarrow \ell^+\ell^-\gamma\gamma$

[8] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \rightarrow \gamma\gamma\,\Upsilon(2S)) \times 2\,B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (5.03 \pm 0.94 \pm 0.63) \times 10^{-4}$, and $B(\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P)) = 0.135 \pm 0.003 \pm 0.017$.

[9] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \rightarrow \gamma\chi_{b2}(2P)) = (11.1 \pm 0.5 \pm 0.4)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b2}(2P)$ REFERENCES

CRAWFORD 92B PL B294 139 +Fulton (CLEO Collab.)
HEINTZ 92 PR D46 1928 +Lee, Franzini+ (CUSB II Collab.)
HEINTZ 91 PRL 66 1563 +Kaarsberg+ (CUSB Collab.)
MORRISON 91 PRL 67 1696 +Schmidt+ (CLEO Collab.)
NARAIN 91 PRL 66 3113 +Lovelock+ (CUSB Collab.)

OTHER RELATED PAPERS

EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\Upsilon(3S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(3S)$ MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
10.3553±0.0005	[1] BARU 86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(3S)$ WIDTH

VALUE (keV)	DOCUMENT ID
26.3±3.5 OUR EVALUATION	See the Note on Width Determinations of the Υ states

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\Upsilon(2S)$anything	(10.6 ±0.8) %	
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.8 ±0.6) %	S=2.2
Γ_3	$\Upsilon(2S)\pi^0\pi^0$	(2.00±0.32) %	
Γ_4	$\Upsilon(2S)\gamma\gamma$	(5.0 ±0.7) %	
Γ_5	$\Upsilon(1S)\pi^+\pi^-$	(4.48±0.21) %	
Γ_6	$\Upsilon(1S)\pi^0\pi^0$	(2.06±0.28) %	
Γ_7	$\Upsilon(1S)\eta$	< 2.2 × 10^{-3}	CL=90%
Γ_8	$\mu^+\mu^-$	(1.81±0.17) %	
Γ_9	e^+e^-	seen	
	Radiative decays		
Γ_{10}	$\gamma\chi_{b2}(2P)$	(11.4 ±0.8) %	S=1.3
Γ_{11}	$\gamma\chi_{b1}(2P)$	(11.3 ±0.6) %	
Γ_{12}	$\gamma\chi_{b0}(2P)$	(5.4 ±0.6) %	S=1.1

$\Upsilon(3S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_0\Gamma_9/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.45±0.03±0.03	[2] GILES 84B	CLEO	$e^+e^- \to$ hadrons

[2] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

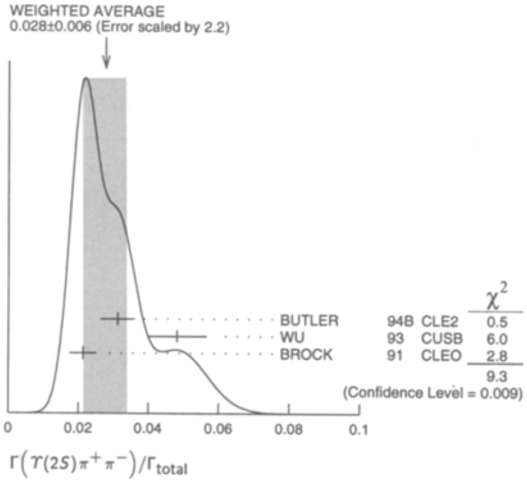
$\Upsilon(3S)$ BRANCHING RATIOS

$\Gamma(\Upsilon(2S)\text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.106 ±0.008 OUR AVERAGE				
0.1023±0.0105	4625	[3,4,5] BUTLER 94B	CLE2	$e^+e^- \to \ell^+\ell^- X$
0.111 ±0.012	4891	[4,5,6] BROCK 91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(2S)\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.028 ±0.006 OUR AVERAGE	Error includes scale factor of 2.2. See the ideogram below.			
0.0312±0.0049	980	[3,7] BUTLER 94B	CLE2	$e^+e^- \to \pi^+\pi^-\ell^+\ell^-$
0.0482±0.0065±0.0053	138	[6] WU 93	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.0213±0.0038	974	[6] BROCK 91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.031 ±0.020	5	MAGERAS 82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$



$\Gamma(\Upsilon(2S)\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0200±0.0032 OUR AVERAGE				
0.0216±0.0039		[7,8] BUTLER 94B	CLE2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.017 ±0.005 ±0.002	10	[9] HEINTZ 92	CSB2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(2S)\gamma\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0502±0.0069	[7] BUTLER 94B	CLE2	$e^+e^- \to \ell^+\ell^- 2\gamma$

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0448±0.0021 OUR AVERAGE				
0.0452±0.0035	11830	[4] BUTLER 94B	CLE2	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.0446±0.0034±0.0050	451	[4] WU 93	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.0446±0.0030	11221	[4] BROCK 91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.049 ±0.010	22	GREEN 82	CLEO	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.039 ±0.013	26	MAGERAS 82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0206±0.0028 OUR AVERAGE				
0.0199±0.0034	56	[4] BUTLER 94B	CLE2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.022 ±0.004 ±0.003	33	[10] HEINTZ 92	CSB2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	BROCK 91	CLEO	$e^+e^- \to \pi^+\pi^-\pi^0\ell^+\ell^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0181±0.0017 OUR AVERAGE				
0.0202±0.0019±0.0033		CHEN 89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0173±0.0015±0.0011		KAARSBERG 89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.033 ±0.013 ±0.007	1096	ANDREWS 83	CLEO	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\gamma\chi_{b2}(2P))/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.114±0.008 OUR AVERAGE	Error includes scale factor of 1.3.			
0.111±0.005±0.004	10319	[11] HEINTZ 92	CSB2	$e^+e^- \to \gamma$
0.135±0.003±0.017	30741	MORRISON 91	CLE2	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b1}(2P))/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.113±0.006 OUR AVERAGE				
0.115±0.005±0.005	11147	[11] HEINTZ 92	CSB2	$e^+e^- \to \gamma$
$0.105^{+0.003}_{-0.002}\pm0.013$	25759	MORRISON 91	CLE2	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(2P))/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.054±0.006 OUR AVERAGE	Error includes scale factor of 1.1.				
0.060±0.004±0.006	4959	[11] HEINTZ	92	CSB2	$e^+e^- \to \gamma$
$0.049^{+0.003}_{-0.004}\pm0.006$	9903	MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[3] Using B($\Upsilon(2S) \to \Upsilon(1S)\gamma\gamma$) = (0.038 ± 0.007)%, and B($\Upsilon(2S) \to \Upsilon(1S)\pi^0\pi^0$) = (1/2)B($\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$).

[4] Using B($\Upsilon(1S) \to \mu^+\mu^-$) = (2.48 ± 0.06)%. With the assumption of $e\mu$ universality.

[5] Using B($\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$) = (18.5 ± 0.8)%.

[6] Using B($\Upsilon(2S) \to \mu^+\mu^-$) = (1.31 ± 0.21)%, B($\Upsilon(2S) \to \Upsilon(1S)\gamma\gamma$)×2B($\Upsilon(1S) \to \mu^+\mu^-$) = (0.188 ± 0.035)%, and B($\Upsilon(2S) \to \Upsilon(1S)\pi^0\pi^0$)×2B($\Upsilon(1S) \to \mu^+\mu^-$) = (0.436 ± 0.056)%. With the assumption of $e\mu$ universality.

[7] From the exclusive mode.

[8] B($\Upsilon(2S) \to \mu^+\mu^-$) = (1.31 ± 0.21)% and assuming $e\mu$ universality.

[9] B($\Upsilon(2S) \to \mu^+\mu^-$) = (1.44 ± 0.10)% and assuming $e\mu$ universality. Supersedes HEINTZ 91.

[10] Using B($\Upsilon(1S) \to \mu^+\mu^-$) = (2.57 ± 0.07)% and assuming $e\mu$ universality. Supersedes HEINTZ 91.

[11] Supersedes NARAIN 91.

$\Upsilon(3S)$ REFERENCES

BUTLER 94B PR D49 40 +Fu, Kalbfleisch, Lambrecht+ (CLEO Collab.)
WU 93 PL B301 307 +Franzini, Kanekal+ (CUSB Collab.)
HEINTZ 92 PR D46 1928 +Lee, Franzini+ (CUSB II Collab.)
BROCK 91 PR D43 1448 +Ferguson+ (CLEO Collab.)
HEINTZ 91 PRL 66 1563 +Kaarsberg+ (CUSB Collab.)
MORRISON 91 PRL 67 1696 +Schmidt+ (CLEO Collab.)
NARAIN 91 PRL 66 3113 +Lovelock+ (CUSB Collab.)
CHEN 89B PR D39 3528 +McIlwain, Miller+ (CLEO Collab.)
KAARSBERG 89 PRL 62 2077 +Heintz+ (CUSB Collab.)
BUCHMUEL... 88 HE e^+e^- Physics 412 Buchmueller, Cooper (HANN, DESY, MIT)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
BARU 86B ZPHY C32 622 +Blinov, Bondar, Bukin+ (NOVO)
KURAEV 85 SJNP 41 466 +Fadin (NOVO)
Translated from YAF 41 733.
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
GILES 84B PR D29 1285 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
ANDREWS 83 PRL 50 807 +Avery, Berkelman, Cassel+ (CLEO Collab.)
GREEN 82 PRL 49 617 +Sannes, Skubic, Snyder+ (CLEO Collab.)
MAGERAS 82 PL 118B 453 +Herb, Imlay+ (COLU, CORN, LSU, MPIM, STON)

OTHER RELATED PAPERS

ALEXANDER 89 NP B320 45 +Bonvicini, Drell, Frey, Luth (LBL, MICH, SLAC)
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
GILES 84B PR D29 1285 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)
PETERSON 82 PL 114B 277 +Giannini, Lee-Franzini+ (CUSB Collab.)
KAPLAN 78 PRL 40 435 +Appel, Herb, Horn+ (STON, FNAL, COLU)
YOH 78 PRL 41 684 +Herb, Horn, Lederman+ (COLU, FNAL, STON)
COBB 77 PL 72B 273 +Iwata, Fabjan+ (BNL, CERN, SYRA, YALE)
HERB 77 PRL 39 252 +Horn, Lederman, Appel, Ito+ (COLU, FNAL, STON)
INNES 77 PRL 39 1240 +Appel, Brown, Herb, Horn+ (COLU, FNAL, STON)

$\Upsilon(4S)$
or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(4S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.5800±0.0035	[1] BEBEK	87	CLEO	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.5774±0.0010	[2] LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

[1] Reanalysis of BESSON 85.

[2] No systematic error given.

$\Upsilon(4S)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10.0±2.8±2.7	[3] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20 ±2 ±4	BESSON	85	CLEO	$e^+e^- \to$ hadrons
25 ±2.5	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

[3] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.

$\Upsilon(4S)$ DECAY MODES

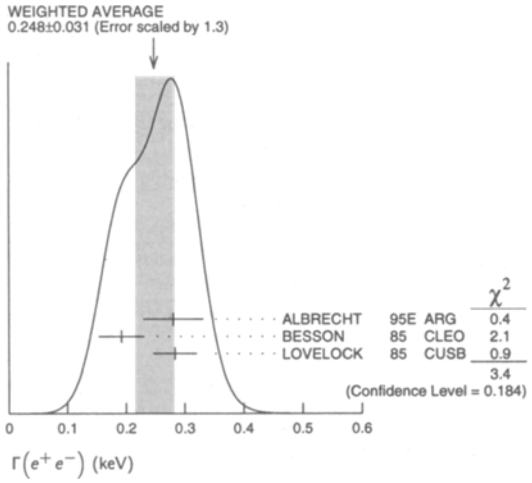
	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$B\bar{B}$	> 96 %	95%
Γ_2	non-$B\bar{B}$	< 4 %	95%
Γ_3	e^+e^-	(2.8±0.7) × 10^{-5}	
Γ_4	$J/\psi(3097)$anything	(2.2±0.7) × 10^{-3}	
Γ_5	D^{*+} anything + c.c.	< 7.4 %	90%
Γ_6	ϕanything	< 2.3 × 10^{-3}	90%
Γ_7	$\Upsilon(1S)$anything	< 4 × 10^{-3}	90%

$\Upsilon(4S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.248±0.031 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
0.28 ±0.05 ±0.01	[4] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons
0.192±0.007±0.038	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.283±0.037	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

[4] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.



$\Upsilon(4S)$ BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
2.77±0.50±0.49	[5] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons

[5] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.

$\Gamma(J/\psi(3097)\text{anything})/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0022±0.0006±0.0004	ALEXANDER	90C	CLEO	e^+e^-

$[\Gamma(D^{*+}\text{anything}) + \Gamma(\text{c.c.})]/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.074	90	[6] ALEXANDER	90C	CLEO	e^+e^-

[6] For $x >$ 0.473.

$\Gamma(\phi\text{anything})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0023	90	[7] ALEXANDER	90C	CLEO	e^+e^-

[7] For $x >$ 0.52.

$\Gamma(\Upsilon(1S)\text{anything})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	ALEXANDER	90C	CLEO	e^+e^-

$\Gamma(\text{non-}B\bar{B})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	95	BARISH	96B	CLEO	e^+e^-

$\Upsilon(4S)$ REFERENCES

BARISH 96B PRL 76 1570 +Chadha, Chan, Eigen+ (CLEO Collab.)
ALBRECHT 95E ZPHY C65 619 +Hamacher+ (ARGUS Collab.)
ALEXANDER 90C PRL 64 2226 +Artuso+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
BESSON 85 PRL 54 381 +Green, Namjoshi, Sannes+ (CLEO Collab.)
LOVELOCK 85 PRL 54 377 +Horstkotte, Klopfenstein+ (CUSB Collab.)
LEYAOUANC 77 PL B71 397 +Oliver, Pene, Raynal (ORSAY)

OTHER RELATED PAPERS

HENDERSON 92 PR D45 2212 +Kinoshita, Pipkin, Procario+ (CLEO Collab.)
ANDREWS 80B PRL 45 219 +Berkelman, Cabenda, Cassel+ (CLEO Collab.)
FINOCCHI... 80 PRL 45 222 Finocchiaro, Giannini, Lee-Franzini+ (CUSB Collab.)

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(10860)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.865±0.008 OUR AVERAGE	Error includes scale factor of 1.1.			
10.868±0.006±0.005	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
10.845±0.020	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
110±13 OUR AVERAGE				
112±17±23	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
110±15	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(2.8\pm0.7)\times10^{-6}$

$\Upsilon(10860)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.31 ±0.07 OUR AVERAGE	Error includes scale factor of 1.3.			
0.22 ±0.05 ±0.07	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
0.365±0.070	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(10860)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(11020)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
11.019±0.008 OUR AVERAGE				
11.019±0.005±0.007	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
11.020±0.030	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
79±16 OUR AVERAGE				
61±13±22	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
90±20	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.6\pm0.5)\times10^{-6}$

$\Upsilon(11020)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.130±0.030 OUR AVERAGE				
0.095±0.03 ±0.035	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
0.156±0.040	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

$\Upsilon(11020)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

NON-$q\bar{q}$ CANDIDATES

We include here mini-reviews and reference lists on gluonium and other non-$q\bar{q}$ candidates. See also $N\bar{N}$(1100–3600) for possible bound states.

NON-$q\bar{q}$ MESONS

Written March 1998 by R. Landua (CERN).

The constituent quark model describes the observed meson spectrum as bound $q\bar{q}$ states grouped into SU(3) flavour nonets. The existence of gluon self-coupling in QCD suggests that additional bound states of gluons (glueballs gg, ggg) or hybrids ($q\bar{q}g$) might exist. Another possible kind of non-$q\bar{q}$ mesons is multiquark states ($qq\bar{q}\bar{q}$, or $q\bar{q}$-$q\bar{q}$).

A glueball has no place in a $q\bar{q}$ nonet, it is a flavour-singlet, produced mainly in gluon-rich channels (radiative $J/\psi(1S)$ decays, antiproton-proton annihilation), and has a small gamma-gamma coupling. However, mixing with $q\bar{q}$ mesons of the same quantum numbers will modify the expected glueball signatures, such as flavour-blind decay modes. If the mixing is large, only the finding of more states than predicted by the quark model remains a clear signal for a non-$q\bar{q}$ state. Theoretical calculations based on lattice gauge theory and QCD sum rules agree that the lightest glueball should be a scalar resonance ($J^{PC} = 0^{++}$) with a mass of 1600 ± 150 MeV (BALI 93, SEXTON 95), followed by a tensor (2^{++}) and a pseudoscalar (0^{-+}) glueball in the 2000–2500 MeV mass region (SZCZEPANIAK 96).

Hybrid mesons are $q\bar{q}$ states combined with a gluonic excitation, allowing exotic (non-$q\bar{q}$) quantum numbers such as $J^{PC} = 1^{-+}$). Hybrids span flavour nonets. In flux tube models, they are predicted to have characteristic decay modes into a pair of $S^-(l=0)$ and $P^-(l=1)$ wave mesons (ISGUR 85, CLOSE 95). The lightest hybrid nonets are expected in the 1500–2000 MeV mass range in the flux tube model and the ground state around 2000 MeV in lattice gauge theories (LACOCK 97). Charm hybrids ($c\bar{c}g$) are expected in the 4000–4400 MeV mass range and are attractive experimentally since they may appear as supernumerary states in the predictable charmonium spectrum.

Multiquark states might exist as a colour-singlet configuration of four or more quarks. A four-quark state can be either baglike ($qq\bar{q}\bar{q}$) or like a meson-meson bound state ($q\bar{q}$-$q\bar{q}$). Several well-established non-$q\bar{q}$ candidates have masses close to meson-meson thresholds. Examples include the $f_0(980)$ (close to the $K\overline{K}$ threshold), the $f_1(1420)$ ($K\overline{K}^*$), the $f_2(1565)$ and $f_0(1500)(\omega\omega$ and $\rho\rho)$, the $f_J(1710)$ ($K^*\overline{K}^*$), and the $\psi(4040)$ ($D^*\overline{D}^*$).

The following discussion is restricted to well-established resonances which are difficult to interpret as conventional $q\bar{q}$ states. We do not see it as our task to discuss theoretical interpretations of the candidates, but merely to summarize the observations of possible relevance. See also the corresponding Note in the 1996 issue of *Review of Particle Physics.*

Resonances with exotic quantum numbers

The first direct evidence for a non-$q\bar{q}$ state is the exotic $J^{PC} = 1^{-+}$ isovector resonance $\hat{\rho}(1405)$. It has been clearly observed in $\bar{p}d$ annihilation at rest (ABELE 98B), corroborating earlier evidence from πp scattering experiments (ALDE 88B, THOMPSON 97). The $\hat{\rho}(1405)$ is observed as a resonant ($\eta\pi^-$) P-wave with a width of 200–300 MeV. There is weaker evidence for a $J^{PC} = 1^{-+}$ state around 1900 MeV (LEE 94).

The mass of the $\hat{\rho}(1405)$ is lower than expected by the flux tube model and lattice gauge theories for a hybrid meson, and its decay into two S-wave mesons does not correspond to the expected hybrid decay pattern. A 1^{-+} hybrid around 1400 MeV is, however, predicted by the bag model (BARNES 83). Whatever the correct interpretation will be (hybrid or four-quark state), it is expected to be part of a multiplet in the same mass region, and its identification will be an important goal for future experiments.

A resonance-like structure has been observed in $\gamma\gamma$ collisions near the $\rho\rho$ threshold, decaying into $\rho^0\rho^0$ and $\rho^+\rho^-$, and with a dominating 2^{++} partial wave. The small relative branching ratio $\rho^+\rho^-/\rho^0\rho^0$ (1:4) (ALBRECHT 91F) requires both $I = 0$ and $I = 2$ for the $\rho\rho$ system, which might be due to the presence of a $qq\bar{q}\bar{q}$ resonance with $I = 2$ (ACHASOV 90).

Scalar glueball

Four isoscalar resonances with $J^{PC} = 0^{++}$ are considered as well-established: the σ or f_0(400–1200), a very broad structure with a width of 600–1000 MeV, the $f_0(980)$, the $f_0(1370)$, and the $f_0(1500)$. Another isoscalar, the $f_J(1710)$, may have spin $J = 0$ or 2.

In the quark model, one expects two scalar nonets ($1\,^3P_0$ and $2\,^3P_0$) below 2000 MeV. However, the spectrum of scalar $q\bar{q}$ resonances may be strongly distorted by the opening of inelastic thresholds (TORNQVIST 96). For a detailed discussion, see the Note on scalar mesons under the $f_0(1370)$.

Several models interpret the $f_0(1500)$ as a supernumerary scalar state due to a glueball mixed with $q\bar{q}$ states in the same mass region (see for example AMSLER 96). This is based on the observation that both the $f_0(1370)$ and the $f_0(1500)$ have similar decay properties (mainly to light quarks), while the quark model expects the heavier resonance to couple strongly to strange quarks. The $f_0(1500)$ has been observed in 4π (ABELE 96), 2π (AMSLER 95B, BERTIN 98), $\eta\eta$ (AMSLER 95C), $\eta\eta'(958)$ (AMSLER 94E), and—weakly—in $K\overline{K}$ decays (ABELE 96B). The $f_0(1500)$ is observed in gluon-rich reactions, such as central production (ALDE 88, BARBERIS 97B), and in radiative $J/\psi(1S)$ decay, while it is not seen in gamma-gamma fusion (ACCIARRI 95J).

The key issue is the identification of the $^3P_0$ ($s\bar{s}$)-like state in the 1600–2000 MeV mass region. This might be the $f_J(1710)$, if spin 0 is confirmed. In radiative $J/\psi(1S)$ decays, both spin 0 and spin 2 components are found in the $f_J(1710)$ mass region, while the resonance observed in central production has spin 2.

An $f_0(1710)$ has also been suggested for the ground state scalar glueball (SEXTON 95). See the Note on $f_J(1710)$.

Tensor glueball

The twol $^3P_2$ $q\overline{q}$ states are very likely the $f_2(1270)$ and $f'_2(1525)$. In the 1800–2400 MeV mass range, one expects three more tensor nonets: the 2 $^3P_2$ and 3 $^3P_2$ radial excitations, and the 1 $^3F_4$ nonet, i.e. six isoscalar 2^{++} resonances. They are all expected to have widths above 100 MeV. There is indeed evidence for several broad resonances in the 1800–2400 MeV region, but the experimental information is too sparse to make a meaningful assignment to $q\overline{q}$ nonets. There is at present no compelling reason to assume that any of these states is a non-$q\overline{q}$ state.

Two states below 2000 MeV, the $f_2(1565)$ and the $f_J(1710)$, are hard to accommodate in the quark model, because their masses are too close to the 1 $^3P_2$ ground state to be members of the 2 $^3P_2$ nonet. The $f_2(1565)$ has only been observed in $p\overline{p}$ annihilation, decaying to $\pi\pi$ (MAY 90, BERTIN 98). The proximity of the $\rho\rho$ and $\omega\omega$ thresholds suggest a possible interpretation as a meson-meson bound state. The $f_J(1710)$ has a well-established 2^{++} component. It is prominently observed in radiative $J/\psi(1S)$ decays, and in central production. It is observed to decay into $K\overline{K}$ (BAI 96C, LONGACRE 86), and its proximity to the $K^*\overline{K}^*$ threshold suggests again a meson-meson bound state.

The narrow $f_2(2220)$ still needs confirmation. There are also still doubts whether it has spin 2 or spin 4. The experimental evidence from $J/\psi(1S)$ radiative decays, πp and Kp scattering is inconclusive. It has not been observed in $p\overline{p}$ annihilation (BARNES 93). If it exists, it couples mainly to strange quark final states, and if spin 2 is confirmed, its prominence in radiative $J/\psi(1S)$ decays and its small width would make it a good glueball candidate.

Pseudoscalar mesons

Four pseudoscalar $I = 0$ resonances are well established below 1500 MeV: η, $\eta'(958)$, $\eta(1295)$, and $\eta(1440)$. It would be natural to identify the latter two with the $u\overline{u} + d\overline{d}$ and $s\overline{s}$ first radial excitations and $s\overline{s}$ of the $^1S_0$ ground states. Since the $\pi(1300)$ and the $\eta(1295)$ have nearly the same masses, the $\eta(1295)$ can be assigned to the $(u\overline{u} + d\overline{d})$ 2 $^1S_0$ state. The crucial issue is the identification of the $(s\overline{s})$ 2 $^1S_0$ state. An assignment to the $\eta(1440)$ is not evident. The $\eta(1440)$ is prominently produced in radiative $J/\psi(1S)$ decays and hence expected to have some glueball admixture, and it is mainly produced in $s\overline{s}$ depleted reactions, such as πp scattering, $p\overline{p}$ annihilation, or radiative $J/\psi(1S)$ decays. There is—albeit weak—evidence that the $\eta(1440)$ is made of two resonances with only about 50–100 MeV difference in mass, and with similar widths, the lower mass state decaying to $a_0(980)\pi$ and $\eta\pi\pi$, the higher mass state to $K^*\overline{K}$. It is therefore conceivable that the higher mass state is the $s\overline{s}$ member of the 2 $^1S_0$ nonet (see the Note on $\eta(1440)$).

The $\pi(1800)$ is surprisingly narrow (if interpreted as the second radial excitation of the π). It decays frequently via a pair of S- and P-wave mesons (AMELIN 95B, 96B), which is a signature expected for a hybrid meson.

Axial-vector mesons

The $f_1(1285)$ and $f_1(1420)$ are the two well-established axial-vector resonances. The $f_1(1510)$ still needs confirmation (see the Note on the $f_1(1510)$ under the $\eta(1440)$). The $f_1(1285)$ has the expected properties of the isoscalar $u\overline{u} + d\overline{d}$ member of a ground state $^3P_1$ nonet. The $f_1(1420)$ has a dominant $K\overline{K}^*$ coupling, as expected for the corresponding $s\overline{s}$ member. In πp scattering, $p\overline{p}$ annihilation at rest from P waves (BERTIN 97) and radiative $J/\psi(1S)$ decays, the $f_1(1420)$ is produced together with the $\eta(1440)$, which gave rise to the former E/ι puzzle. In central production, only the $f_1(1420)$ state is produced (BARBERIS 97C).

Presently, there is no strong evidence for an exotic axial-vector state. However, if the $f_1(1510)$ state is corroborated, the proximity of the $f_1(1420)$ mass to the KK^* threshold suggests a $K\overline{K}^*$ meson-bound state or a threshold enhancement.

Non-$q\bar{q}$ Candidates

OMITTED FROM SUMMARY TABLE

NON-$q\bar{q}$ CANDIDATES REFERENCES

ABELE	98B	PL B423 175	A. Abele, Adomeit, Amsler+	(Crystal Barrel Collab.)
BERTIN	98	PR D57 55	A. Bertin, Bruschi, Capponi+	(OBELIX Collab.)
ACHASOV	97C	PR D56 4084	N.N. Achasov+	
ACHASOV	97D	PR D56 203	N.N. Achasov+	
ANISOVICH	97B	ZPHY A357 123	A.V. Anisovich+	(PNPI)
ANISOVICH	97C	PL B413 137		
ANISOVICH	97E	PAN 60 1892	A.V. Anisovich+	(PNPI)
		Translated from YAF 60 2065.		
BARBERIS	97	PL B397 339	D. Barberis+	(WA102 Collab.)
BARBERIS	97B	PL B413 217	D. Barberis+	(WA102 Collab.)
BARBERIS	97C	PL B413 225	D. Barberis+	(WA102 Collab.)
BERTIN	97	PL B400 226	+Bruschi, Capponi+	(OBELIX Collab.)
BOGLIONE	97	PRL 79 1998	M. Boglione+	
BUGG	97	PL B396 295	D.V. Bugg+	
CLOSE	97	PL B397 333	F. Close+	(RAL, BIRM)
CLOSE	97B	PR D55 5749	F. Close+	(RAL, RUTG, BEIJT)
GERASYUTA	97	ZPHY C74 325	S.M. Gerasyuta+	
HOU	97	PR D55 6952	Wei-Shu Hou	
KISSLINGER	97	PL B410 1	L.S. Kisslinger+	
LACOCK	97	PL B401 308	P. Lacock+	(EDIN, LIVP)
PAGE	97	PL B402 183	P.R. Page	
PAGE	97B	NPB 495 268	P.R. Page	
PAGE	97C	PL B415 205	P.R. Page	(CEBAF)
THOMPSON	97	PRL 79 1630	+Adams+	(E852 Collab.)
YAN	97	JP G23 L33	Y. Yan+	
ABELE	96	PL B380 453	+Adomeit, Amsler+	(Crystal Barrel Collab.)
AMELIN	96B	PAN 59 976	+Berdnikov, Bityukov+	(SERP, TBIL)
		Translated from YAF 59 1021.		
AMSLER	96	PR D53 295	+Close	(ZURI, RAL)
BAI	96C	PRL 77 3959	J.Z. Bai+	(BES Collab.)
BAJC	96	ZPHY A356 187	B. Bajc+	
CLOSE	96	PL B366 323	+Page	(RAL)
SZCZEPANIAK	96	PRL 76 2011	A. Szczepaniak+	(NCARO)
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
AMSLER	95E	PL B353 385	+Close	(ZURI, RAL)
AMSLER	95F	PL B358 389	+Armstrong, Urner+	(Crystal Barrel Collab.)
BERTIN	95	PL B361 187	+Bruschi+	(OBELIX Collab.)
BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
CLOSE	95	NP B443 233	+Page	(RAL)
PROKOSHKIN	95B	PAN 58 606	+Sadovski	(SERP)
		Translated from YAF 58 662.		
PROKOSHKIN	95C	PAN 58 853	+Sadovski	(SERP)
		Translated from YAF 58 921.		
SEXTON	95	PRL 75 4563	+Vaccarino, Weingarten+	(IBM)
ALBRECHT	94Z	PL B332 451	+Ehrlichmann+	(ARGUS Collab.)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	94	PL B323 233	+Armstrong+	(Crystal Barrel Collab.)
BERDNIKOV	94	PL B337 219	+Bityukov+	(SERP, TBIL)
LEE	94	PL B323 227	+Chung, Kirk+	(BNL, IND, KYUN, MASD, RICE)
TORNQVIST	94	ZPHY C61 525	Tornquist	(HELS)
ALEEV	93	PAN 56 1358	+Balandin+	(BIS-2 Collab.)
		Translated from YAF 56 100.		
AOYAGI	93	PL B314 246	+Fukui, Hasegawa+	(BKEI Collab.)
BALI	93	PL B309 378	+Schilling, Hulsebo, Irving, Michael+	(LIVP)
BARNES	93	PL B309 469	+Birien, Breunlich	(PS185 Collab.)
DONNACHIE	93	ZP C60 187	+Kalashnikova, Clegg	(BNL)
ERICSON	93	PL B309 426	+Karl	(CERN)
MANOHAR	93	NP B399 17	+Wise	(MIT)
AMSLER	92	PL B291 347	+Augustin, Baker+	(Crystal Barrel Collab.)
BARNES	92	PR D46 131	+Swanson	(ORNL)
DOOLEY	92	PL B275 478	+Swanson, Barnes	(ORNL)
ALBRECHT	91F	ZPHY C50 1	+Appuan, Paulini, Funk+	(ARGUS Collab.)
DOVER	91	PR C43 379	+Gutsche, Faessler	(BNL)
FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
TORNQVIST	91	PRL 67 556		(HELS)
ACHASOV	90	TF 20 (178)	+Shestakov	(NOVM)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEIDH, WARS)
BURNETT	90	ARNPS 46 332	+Sharpe	(RAL)
LONGACRE	90	PR D42 874		(BNL)
MAY	90	ZPHY C46 203	+Duch, Heel+	(ASTERIX Collab.)
WEINSTEIN	90	PR D41 2236	+Isgur	(TNTO)
ALDE	89	PL B216 447	+Binon, Bricman, Donskov+	(SERP, BELG, LANL, LAPP)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
MAY	89	PL B225 450	+Duch, Heel+	(ASTERIX Collab.)
ACHASOV	88	PL B207 199	+Kozhevnikov	(NOVM)
AIHARA	88	PR D37 28	+Alston, Avery, Barbaro-Galtieri+	(TPC-2γ Collab.)
ALDE	88	PL B201 160	+Bellazzini, Binon+	(SERP, BELG, LANL, LAPP, PISA)
ALDE	88B	PL B205 397	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
BERGER	88B	ZPHY C38 521	+Klovning, Burger+	(PLUTO Collab.)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, MASD)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
IDDIR	88	PL B205 564	+Le Yaouanc, Ono+	(ORSAY, TOKY)
ACHASOV	87	ZPHY C36 161	+Karnakov, Shestakov	(NOVM)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
CLOSE	*87*	*RPP 51 833*		*(RHEL)*
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+)
BOURQUIN	86	PL B172 113	+Brown+	(GEVA, RAL, HEIDP, LAUS, BRIS, CERN)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, MASD)
ISGUR	85	PRL 54 869	+Kokorski, Patou	(TNTO)
LEYAOUANC	85	ZPHY C28 309	+Olivek, Pene, Raynal, Ono	(ORSAY)
BEHREND	84E	ZPHY C21 205	+Achenberg, Deboer+	(CELLO Collab.)
BARNES	83	NP B224 241	T. Barnes+	(RAL, LOUV)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
AIHARA	82	PR D37 28	+Alston, Avery, Barbaro-Galtieri+	(TPC Collab.)
ALTHOFF	82	ZPHY C16 13	+Boerner, Burkhardt+	(TASSO Collab.)
BARNES	82	PL B116 365	+Close	(RHEL)
BURKE	81	PL B103 153	+Abrams, Alam, BLocher+	(Mark II Collab.)
BRANDELIK	80B	PL B97 448	+Boerner, Burkhard+	(TASSO Collab.)
GUTBROD	79	ZP C1 391	+Kramer, Rumpf	(DESY)
JAFFE	77	PR D15 267,281		(MIT)
VOLOSHIN	76	JETPL 23 333	+Okun	(ITEP)
		Translated from ZETFP 23 369.		
BAILLON	67	NC 50A 393	+Edwards, D'Andlau, Astier+	(CERN, CDEF, IRAD)

N BARYONS ($S = 0, I = 1/2$)

Δ BARYONS ($S = 0, I = 3/2$)

Λ BARYONS ($S = -1, I = 0$)

Σ BARYONS ($S = -1, I = 1$)

Ξ BARYONS ($S = -2, I = 1/2$)

Ω BARYONS ($S = -3, I = 0$)

CHARMED BARYONS ($C = +1$)

BOTTOM (BEAUTY) BARYON ($B = -1$)

Notes in the Baryon Listings

N BARYONS
$(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

$\boxed{p}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnote. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
938.27231±0.00028	[1] COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
938.2796 ±0.0027	COHEN 73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.007276470 \pm 0.000000012$ u.

$\overline{p}$ MASS

See, however, the next entry in the Listings, which establishes the $\overline{p}$ mass much more precisely.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
938.30 ±0.13	ROBERTS 78	CNTR	
938.229±0.049	ROBERSON 77	CNTR	
938.179±0.058	HU 75	CNTR	Exotic atoms
938.3 ±0.5	BAMBERGER 70	CNTR	

$\overline{p}/p$ CHARGE-TO-MASS RATIO, $|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p})$

A test of *CPT* invariance. Listed here are measurements involving the *inertial* masses. For a discussion of what may be inferred about the ratio of $\overline{p}$ and p *gravitational* masses, see ERICSON 90; they obtain an upper bound of 10^{-6}–10^{-7} for violation of the equivalence principle for $\overline{p}$'s.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
1.0000000015±0.0000000011	[2] GABRIELSE 95	TRAP	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.000000023 ±0.000000042	[3] GABRIELSE 90	TRAP	Penning trap

[2] Equation (2) of GABRIELSE 95 should read $M(\overline{p})/M(p) = 0.999\,999\,99\underline{8}5\,(11)$ (G. Gabrielse, private communication).

[3] GABRIELSE 90 also measures $m_{\overline{p}}/m_{e^-} = 1836.152660 \pm 0.000083$ and $m_p/m_{e^-} = 1836.152680 \pm 0.000088$. Both are completely consistent with the 1986 CODATA (COHEN 87) value for m_p/m_{e^-} of 1836.152701 ± 0.000037. We use the CODATA values of the masses (they come from an overall fit to a variety of data on the fundamental constants) and don't try to take into account more recent measurements involving the masses.

$(|\frac{q_{\overline{p}}}{m_{\overline{p}}}|-\frac{q_p}{m_p})/|\frac{q}{m}|_{\text{average}}$

A test of *CPT* invariance. Taken from the $\overline{p}/p$ charge-to-mass ratio, above.

VALUE	*DOCUMENT ID*
$(1.5\pm1.1) \times 10^{-9}$ OUR EVALUATION	

$|q_p + q_{\overline{p}}|/e$

A test of *CPT* invariance. Note that the $\overline{p}/p$ charge-to-mass ratio, given above, is much better determined. See also a similar test involving the electron.

VALUE	*DOCUMENT ID*	*TECN*
$<2 \times 10^{-5}$	[4] HUGHES 92	RVUE

[4] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.

$|q_p + q_e|/e$

See DYLLA 73 for a summary of experiments on the neutrality of matter. See also "*n* CHARGE" in the neutron Listings.

VALUE	*DOCUMENT ID*	*COMMENT*
$<1.0 \times 10^{-21}$	[5] DYLLA 73	Neutrality of SF_6
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$<0.8 \times 10^{-21}$	MARINELLI 84	Magnetic levitation

[5] Assumes that $q_n = q_p + q_e$.

p MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	*DOCUMENT ID*	*TECN*	*COMMENT*
2.792847386±0.000000063	COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.7928456 ±0.0000011	COHEN 73	RVUE	1973 CODATA value

$\overline{p}$ MAGNETIC MOMENT

A few early results have been omitted.

VALUE (μ_N)	*DOCUMENT ID*	*TECN*	*COMMENT*
−2.800 ±0.008 OUR AVERAGE			
−2.8005±0.0090	KREISSL 88	CNTR	$\overline{p}\,{}^{208}$Pb 11→ 10 X-ray
−2.817 ±0.048	ROBERTS 78	CNTR	
−2.791 ±0.021	HU 75	CNTR	Exotic atoms

$(\mu_p + \mu_{\overline{p}})\,/\,|\mu|_{\text{average}}$

A test of *CPT* invariance. Calculated from the p and $\overline{p}$ magnetic moments, above.

VALUE	*DOCUMENT ID*
$(-2.6\pm2.9) \times 10^{-3}$ OUR EVALUATION	

p ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-23} ecm)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
− 3.7± 6.3		CHO 89	NMR	Tl F molecules
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 400		DZUBA 85	THEO	Uses ^{129}Xe moment
130 ± 200		[6] WILKENING 84		
900 ±1400		[7] WILKENING 84		
700 ± 900	1G	HARRISON 69	MBR	Molecular beam

[6] This WILKENING 84 value includes a finite-size effect and a magnetic effect.

[7] This WILKENING 84 value is more cautious than the other and excludes the finite-size effect, which relies on uncertain nuclear integrals.

p ELECTRIC POLARIZABILITY $\overline{\alpha}_p$

VALUE (10^{-4} fm^3)	*DOCUMENT ID*	*TECN*	*COMMENT*
12.1 ±0.8 ±0.5	[8] MACGIBBON 95	RVUE	global average
• • • We do not use the following data for averages, fits, limits, etc. • • •			
12.5 ±0.6 ±0.9	MACGIBBON 95	CNTR	γp Compton scattering
9.8 ±0.4 ±1.1	HALLIN 93	CNTR	γp Compton scattering
$10.62^{+1.25+1.07}_{-1.19-1.03}$	ZIEGER 92	CNTR	γp Compton scattering
10.9 ±2.2 ±1.3	[9] FEDERSPIEL 91	CNTR	γp Compton scattering

[8] MACGIBBON 95 combine the results of ZIEGER 92, FEDERSPIEL 91, and their own experiment to get a "global average" in which model errors and systematic errors are treated in a consistent way. See MACGIBBON 95 for a discussion.

[9] FEDERSPIEL 91 obtains for the (static) electric polarizability α_p, defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_p\mathbf{E}$, the value $(7.0\pm2.2\pm1.3)\times10^{-4}$ fm^3.

p MAGNETIC POLARIZABILITY $\overline{\beta}_p$

The electric and magnetic polarizabilities are subject to a dispersion sum-rule constraint $\overline{\alpha} + \overline{\beta} = (14.2 \pm 0.5) \times 10^{-4}$ fm^3. Errors here are anticorrelated with those on $\overline{\alpha}_p$ due to this constraint.

VALUE (10^{-4} fm^3)	*DOCUMENT ID*	*TECN*	*COMMENT*
2.1 ±0.8 ±0.5	[10] MACGIBBON 95	RVUE	global average
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.7 ±0.6 ±0.9	MACGIBBON 95	CNTR	γp Compton scattering
4.4 ±0.4 ±1.1	HALLIN 93	CNTR	γp Compton scattering
$3.58^{+1.19+1.03}_{-1.25-1.07}$	ZIEGER 92	CNTR	γp Compton scattering
3.3 ±2.2 ±1.3	FEDERSPIEL 91	CNTR	γp Compton scattering

[10] MACGIBBON 95 combine the results of ZIEGER 92, FEDERSPIEL 91, and their own experiment to get a "global average" in which model errors and systematic errors are treated in a consistent way. See MACGIBBON 95 for a discussion.

p MEAN LIFE

A test of baryon conservation. See the "*p* Partial Mean Lives" section below for limits that depend on decay modes. *p* = proton, *n* = bound neutron.

LIMIT (years)	PARTICLE	DOCUMENT ID		TECN
$>1.6 \times 10^{25}$	***p*, *n***	[11,12] EVANS	77	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>3 \times 10^{23}$	*p*	[12] DIX	70	CNTR
$>3 \times 10^{23}$	*p*, *n*	[12,13] FLEROV	58	

[11] Mean lifetime of nucleons in ^{130}Te nuclei.
[12] Converted to mean life by dividing half-life by ln(2) = 0.693.
[13] Mean lifetime of nucleons in ^{232}Th nuclei.

$\overline{p}$ MEAN LIFE

The best limit by far, that of GOLDEN 79, relies, however, on a number of astrophysical assumptions. The other limits come from direct observations of stored antiprotons. See also "$\overline{p}$ Partial Mean Lives" after "*p* Partial Mean Lives," below.

LIMIT (years)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.28			GABRIELSE	90	TRAP	Penning trap
>0.08	90	1	BELL	79	CNTR	Storage ring
$>1 \times 10^{7}$			GOLDEN	79	SPEC	$\overline{p}/p$, cosmic rays
$>3.7 \times 10^{-3}$			BREGMAN	78	CNTR	Storage ring

p DECAY MODES

Below, for *N* decays, *p* and *n* distinguish proton and neutron partial lifetimes. See also the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1673) for a short review.

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life and B_i is the branching fraction for the mode in question.

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 130 (*n*), > 550 (*p*)	90%
τ_2	$N \to \mu^+\pi$	> 100 (*n*), > 270 (*p*)	90%
τ_3	$N \to \nu\pi$	> 100 (*n*), > 25 (*p*)	90%
τ_4	$p \to e^+\eta$	> 140	90%
τ_5	$p \to \mu^+\eta$	> 69	90%
τ_6	$n \to \nu\eta$	> 54	90%
τ_7	$N \to e^+\rho$	> 58 (*n*), > 75 (*p*)	90%
τ_8	$N \to \mu^+\rho$	> 23 (*n*), > 110 (*p*)	90%
τ_9	$N \to \nu\rho$	> 19 (*n*), > 27 (*p*)	90%
τ_{10}	$p \to e^+\omega$	> 45	90%
τ_{11}	$p \to \mu^+\omega$	> 57	90%
τ_{12}	$n \to \nu\omega$	> 43	90%
τ_{13}	$N \to e^+K$	> 1.3 (*n*), > 150 (*p*)	90%
τ_{14}	$p \to e^+K^0_S$	> 76	90%
τ_{15}	$p \to e^+K^0_L$	> 44	90%
τ_{16}	$N \to \mu^+K$	> 1.1 (*n*), > 120 (*p*)	90%
τ_{17}	$p \to \mu^+K^0_S$	> 64	90%
τ_{18}	$p \to \mu^+K^0_L$	> 44	90%
τ_{19}	$N \to \nu K$	> 86 (*n*), > 100 (*p*)	90%
τ_{20}	$p \to e^+K^*(892)^0$	> 52	90%
τ_{21}	$N \to \nu K^*(892)$	> 22 (*n*), > 20 (*p*)	90%
	Antilepton + mesons		
τ_{22}	$p \to e^+\pi^+\pi^-$	> 21	90%
τ_{23}	$p \to e^+\pi^0\pi^0$	> 38	90%
τ_{24}	$n \to e^+\pi^-\pi^0$	> 32	90%
τ_{25}	$p \to \mu^+\pi^+\pi^-$	> 17	90%
τ_{26}	$p \to \mu^+\pi^0\pi^0$	> 33	90%
τ_{27}	$n \to \mu^+\pi^-\pi^0$	> 33	90%
τ_{28}	$n \to e^+K^0\pi^-$	> 18	90%
	Lepton + meson		
τ_{29}	$n \to e^-\pi^+$	> 65	90%
τ_{30}	$n \to \mu^-\pi^+$	> 49	90%
τ_{31}	$n \to e^-\rho^+$	> 62	90%
τ_{32}	$n \to \mu^-\rho^+$	> 7	90%
τ_{33}	$n \to e^-K^+$	> 32	90%
τ_{34}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{35}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{36}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{37}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{38}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{39}	$p \to e^-\pi^+K^+$	> 20	90%
τ_{40}	$p \to \mu^-\pi^+K^+$	> 5	90%
	Antilepton + photon(s)		
τ_{41}	$p \to e^+\gamma$	> 460	90%
τ_{42}	$p \to \mu^+\gamma$	> 380	90%
τ_{43}	$n \to \nu\gamma$	> 24	90%
τ_{44}	$p \to e^+\gamma\gamma$	> 100	90%
	Three (or more) leptons		
τ_{45}	$p \to e^+e^+e^-$	> 510	90%
τ_{46}	$p \to e^+\mu^+\mu^-$	> 81	90%
τ_{47}	$p \to e^+\nu\nu$	> 11	90%
τ_{48}	$n \to e^+e^-\nu$	> 74	90%
τ_{49}	$n \to \mu^+e^-\nu$	> 47	90%
τ_{50}	$n \to \mu^+\mu^-\nu$	> 42	90%
τ_{51}	$p \to \mu^+e^+e^-$	> 91	90%
τ_{52}	$p \to \mu^+\mu^+\mu^-$	> 190	90%
τ_{53}	$p \to \mu^+\nu\nu$	> 21	90%
τ_{54}	$p \to e^-\mu^+\mu^+$	> 6	90%
τ_{55}	$n \to 3\nu$	> 0.0005	90%
τ_{56}	$n \to 5\nu$		
	Inclusive modes		
τ_{57}	$N \to e^+$anything	> 0.6 (*n*, *p*)	90%
τ_{58}	$N \to \mu^+$anything	> 12 (*n*, *p*)	90%
τ_{59}	$N \to \nu$anything		
τ_{60}	$N \to e^+\pi^0$anything	> 0.6 (*n*, *p*)	90%
τ_{61}	$N \to$ 2 bodies, ν-free		
	$\Delta B = 2$ dinucleon modes		
	The following are lifetime limits per iron nucleus.		
τ_{62}	$pp \to \pi^+\pi^+$	> 0.7	90%
τ_{63}	$pn \to \pi^+\pi^0$	> 2	90%
τ_{64}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{65}	$nn \to \pi^0\pi^0$	> 3.4	90%
τ_{66}	$pp \to e^+e^+$	> 5.8	90%
τ_{67}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{68}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{69}	$pn \to e^+\overline{\nu}$	> 2.8	90%
τ_{70}	$pn \to \mu^+\overline{\nu}$	> 1.6	90%
τ_{71}	$nn \to \nu_e\overline{\nu}_e$	> 0.000012	90%
τ_{72}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 0.000006	90%

$\overline{p}$ DECAY MODES

	Mode	Partial mean life (years)	Confidence level
τ_{73}	$\overline{p} \to e^-\gamma$	> 1848	95%
τ_{74}	$\overline{p} \to e^-\pi^0$	> 554	95%
τ_{75}	$\overline{p} \to e^-\eta$	> 171	95%
τ_{76}	$\overline{p} \to e^-K^0_S$	> 29	95%
τ_{77}	$\overline{p} \to e^-K^0_L$	> 9	95%

p PARTIAL MEAN LIVES

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life for the proton and B_i is the branching fraction for the mode in question.

Decaying particle: *p* = proton, *n* = bound neutron. The same event may appear under more than one partial decay mode. Background estimates may be accurate to a factor of two.

$\tau(N \to e^+\pi)$ τ_1

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>550	***p***	**90**	**0**	**0.7**	[14] BECKER-SZ...	90	IMB3
>130	***n***	**90**	**0**	**<0.2**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 70	*p*	90	0	0.5	BERGER	91	FREJ
> 70	*n*	90	0	≤ 0.1	BERGER	91	FREJ
>260	*p*	90	0	<0.04	HIRATA	89C	KAMI
>310	*p*	90	0	0.6	SEIDEL	88	IMB
>100	*n*	90	0	1.6	SEIDEL	88	IMB
> 1.3	*n*	90	0		BARTELT	87	SOUD
> 1.3	*p*	90	0		BARTELT	87	SOUD
>250	*p*	90	0	0.3	HAINES	86	IMB
> 31	*n*	90	8	9	HAINES	86	IMB
> 64	*p*	90	0	<0.4	ARISAKA	85	KAMI
> 26	*n*	90	0	<0.7	ARISAKA	85	KAMI
> 82	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>250	*p*	90	0	0.2	BLEWITT	85	IMB
> 25	*n*	90	4	4	PARK	85	IMB
> 15	*p*, *n*	90	0		BATTISTONI	84	NUSX
> 0.5	*p*	90	1	0.3	[15] BARTELT	83	SOUD
> 0.5	*n*	90	1	0.3	[15] BARTELT	83	SOUD
> 5.8	*p*	90	2		[16] KRISHNA...	82	KOLR
> 5.8	*n*	90	2		[16] KRISHNA...	82	KOLR
> 0.1	*n*	90			[17] GURR	67	CNTR

[14] This BECKER-SZENDY 90 result includes data from SEIDEL 88.
[15] Limit based on zero events.
[16] We have calculated 90% CL limit from 1 confined event.
[17] We have converted half-life to 90% CL mean life.

$\tau(N \to \mu^+ \pi)$ τ_2

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	***n***	**90**	**0**	**<0.2**	HIRATA	89C	KAMI
>270	***p***	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 81	*p*	90	0	0.2	BERGER	91	FREJ
> 35	*n*	90	1	1.0	BERGER	91	FREJ
>230	*p*	90	0	<0.07	HIRATA	89C	KAMI
> 63	*n*	90	0	0.5	SEIDEL	88	IMB
> 76	*p*	90	2	1	HAINES	86	IMB
> 23	*n*	90	8	7	HAINES	86	IMB
> 46	*p*	90	0	<0.7	ARISAKA	85	KAMI
> 20	*n*	90	0	<0.4	ARISAKA	85	KAMI
> 59	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>100	*p*	90	1	0.4	BLEWITT	85	IMB
> 38	*n*	90	1	4	PARK	85	IMB
> 10	*p*, *n*	90	0		BATTISTONI	84	NUSX
> 1.3	*p*, *n*	90	0		ALEKSEEV	81	BAKS

$\tau(N \to \nu \pi)$ τ_3

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
> 25	***p***	**90**	**32**	**32.8**	HIRATA	89C	KAMI
>100	***n***	**90**	**1**	**3**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 13	*n*	90	1	1.2	BERGER	89	FREJ
> 10	*p*	90	11	14	BERGER	89	FREJ
> 6	*n*	90	73	60	HAINES	86	IMB
> 2	*p*	90	16	13	KAJITA	86	KAMI
> 40	*n*	90	0	1	KAJITA	86	KAMI
> 7	*n*	90	28	19	PARK	85	IMB
> 7	*n*	90	0		BATTISTONI	84	NUSX
> 2	*p*	90	≤ 3		BATTISTONI	84	NUSX
> 5.8	*p*	90	1		[18] KRISHNA...	82	KOLR
> 0.3	*p*	90	2		[19] CHERRY	81	HOME
> 0.1	*p*	90			[20] GURR	67	CNTR

[18] We have calculated 90% CL limit from 1 confined event.
[19] We have converted 2 possible events to 90% CL limit.
[20] We have converted half-life to 90% CL mean life.

$\tau(p \to e^+ \eta)$ τ_4

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>140	***p***	**90**	**0**	**<0.04**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 44	*p*	90	0	0.1	BERGER	91	FREJ
>100	*p*	90	0	0.6	SEIDEL	88	IMB
>200	*p*	90	5	3.3	HAINES	86	IMB
> 64	*p*	90	0	<0.8	ARISAKA	85	KAMI
> 64	*p* (free)	90	5	6.5	BLEWITT	85	IMB
>200	*p*	90	5	4.7	BLEWITT	85	IMB
> 1.2	*p*	90	2		[21] CHERRY	81	HOME

[21] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+ \eta)$ τ_5

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>69	***p***	**90**	**1**	**<0.08**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>26	*p*	90	1	0.8	BERGER	91	FREJ
> 1.3	*p*	90	0	0.7	PHILLIPS	89	HPW
>34	*p*	90	1	1.5	SEIDEL	88	IMB
>46	*p*	90	7	6	HAINES	86	IMB
>26	*p*	90	1	<0.8	ARISAKA	85	KAMI
>17	*p* (free)	90	6	6	BLEWITT	85	IMB
>46	*p*	90	7	8	BLEWITT	85	IMB

$\tau(n \to \nu \eta)$ τ_6

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>54	***n***	**90**	**2**	**0.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>29	*n*	90	0	0.9	BERGER	89	FREJ
>16	*n*	90	3	2.1	SEIDEL	88	IMB
>25	*n*	90	7	6	HAINES	86	IMB
>30	*n*	90	0	0.4	KAJITA	86	KAMI
>18	*n*	90	4	3	PARK	85	IMB
> 0.6	*n*	90	2		[22] CHERRY	81	HOME

[22] We have converted 2 possible events to 90% CL limit.

$\tau(N \to e^+ \rho)$ τ_7

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>75	***p***	**90**	**2**	**2.7**	HIRATA	89C	KAMI
>58	***n***	**90**	**0**	**1.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>29	*p*	90	0	2.2	BERGER	91	FREJ
>41	*n*	90	0	1.4	BERGER	91	FREJ
>38	*n*	90	2	4.1	SEIDEL	88	IMB
> 1.2	*p*	90	0		BARTELT	87	SOUD
> 1.5	*n*	90	0		BARTELT	87	SOUD
>17	*p*	90	7	7	HAINES	86	IMB
>14	*n*	90	9	4	HAINES	86	IMB
>12	*p*	90	0	<1.2	ARISAKA	85	KAMI
> 6	*n*	90	2	<1	ARISAKA	85	KAMI
> 6.7	*p* (free)	90	6	6	BLEWITT	85	IMB
>17	*p*	90	7	7	BLEWITT	85	IMB
>12	*n*	90	4	2	PARK	85	IMB
> 0.6	*n*	90	1	0.3	[23] BARTELT	83	SOUD
> 0.5	*p*	90	1	0.3	[23] BARTELT	83	SOUD
> 9.8	*p*	90	1		[24] KRISHNA...	82	KOLR
> 0.8	*p*	90	2		[25] CHERRY	81	HOME

[23] Limit based on zero events.
[24] We have calculated 90% CL limit from 0 confined events.
[25] We have converted 2 possible events to 90% CL limit.

$\tau(N \to \mu^+ \rho)$ τ_8

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>110	***p***	**90**	**0**	**1.7**	HIRATA	89C	KAMI
> 23	***n***	**90**	**1**	**1.8**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 12	*p*	90	0	0.5	BERGER	91	FREJ
> 22	*n*	90	0	1.1	BERGER	91	FREJ
> 4.3	*p*	90	0	0.7	PHILLIPS	89	HPW
> 30	*p*	90	0	0.5	SEIDEL	88	IMB
> 11	*n*	90	1	1.1	SEIDEL	88	IMB
> 16	*p*	90	4	4.5	HAINES	86	IMB
> 7	*n*	90	6	5	HAINES	86	IMB
> 12	*p*	90	0	<0.7	ARISAKA	85	KAMI
> 5	*n*	90	1	<1.2	ARISAKA	85	KAMI
> 5.5	*p* (free)	90	4	5	BLEWITT	85	IMB
> 16	*p*	90	4	5	BLEWITT	85	IMB
> 9	*n*	90	1	2	PARK	85	IMB

$\tau(N \to \nu\rho)$ τ_9

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>27	**p**	**90**	**5**	**1.5**	HIRATA	89C	KAMI
>19	**n**	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 9	n	90	4	2.4	BERGER	89	FREJ
>24	p	90	0	0.9	BERGER	89	FREJ
>13	n	90	4	3.6	HIRATA	89C	KAMI
>13	p	90	1	1.1	SEIDEL	88	IMB
> 8	p	90	6	5	HAINES	86	IMB
> 2	n	90	15	10	HAINES	86	IMB
>11	p	90	2	1	KAJITA	86	KAMI
> 4	n	90	2	2	KAJITA	86	KAMI
> 4.1	p (free)	90	6	7	BLEWITT	85	IMB
> 8.4	p	90	6	5	BLEWITT	85	IMB
> 2	n	90	7	3	PARK	85	IMB
> 0.9	p	90	2		[26] CHERRY	81	HOME
> 0.6	n	90	2		[26] CHERRY	81	HOME

[26] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+\omega)$ τ_{10}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>45	**p**	**90**	**2**	**1.45**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	p	90	0	1.1	BERGER	91	FREJ
>26	p	90	1	1.0	SEIDEL	88	IMB
> 1.5	p	90	0		BARTELT	87	SOUD
>37	p	90	6	5.3	HAINES	86	IMB
>25	p	90	1	<1.4	ARISAKA	85	KAMI
>12	p (free)	90	6	7.5	BLEWITT	85	IMB
>37	p	90	6	5.7	BLEWITT	85	IMB
> 0.6	p	90	1	0.3	[27] BARTELT	83	SOUD
> 9.8	p	90	1		[28] KRISHNA...	82	KOLR
> 2.8	p	90	2		[29] CHERRY	81	HOME

[27] Limit based on zero events.
[28] We have calculated 90% CL limit from 0 confined events.
[29] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+\omega)$ τ_{11}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	**p**	**90**	**2**	**1.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>11	p	90	0	1.0	BERGER	91	FREJ
> 4.4	p	90	0	0.7	PHILLIPS	89	HPW
>10	p	90	2	1.3	SEIDEL	88	IMB
>23	p	90	2	1	HAINES	86	IMB
> 6.5	p (free)	90	9	8.7	BLEWITT	85	IMB
>23	p	90	8	7	BLEWITT	85	IMB

$\tau(n \to \nu\omega)$ τ_{12}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>43	**n**	**90**	**3**	**2.7**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	n	90	1	0.7	BERGER	89	FREJ
> 6	n	90	2	1.3	SEIDEL	88	IMB
>12	n	90	6	6	HAINES	86	IMB
>18	n	90	2	2	KAJITA	86	KAMI
>16	n	90	1	2	PARK	85	IMB
> 2.0	n	90	2		[30] CHERRY	81	HOME

[30] We have converted 2 possible events to 90% CL limit.

$\tau(N \to e^+K)$ τ_{13}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>150	**p**	**90**	**0**	**<0.27**	HIRATA	89C	KAMI
> 1.3	**n**	**90**	**0**		ALEKSEEV	81	BAKS
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 60	p	90	0		BERGER	91	FREJ
> 70	p	90	0	1.8	SEIDEL	88	IMB
> 77	p	90	5	4.5	HAINES	86	IMB
> 38	p	90	0	<0.8	ARISAKA	85	KAMI
> 24	p (free)	90	7	8.5	BLEWITT	85	IMB
> 77	p	90	5	4	BLEWITT	85	IMB
> 1.3	p	90	0		ALEKSEEV	81	BAKS

$\tau(p \to e^+K^0_S)$ τ_{14}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>76	**p**	**90**	**0**	**0.5**	BERGER	91	FREJ

$\tau(p \to e^+K^0_L)$ τ_{15}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>44	**p**	**90**	**0**	**≤ 0.1**	BERGER	91	FREJ

$\tau(N \to \mu^+K)$ τ_{16}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>120	**p**	**90**	**1**	**0.4**	HIRATA	89C	KAMI
> 1.1	**n**	**90**	**0**		BARTELT	87	SOUD
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 54	p	90	0		BERGER	91	FREJ
> 3.0	p	90	0	0.7	PHILLIPS	89	HPW
> 19	p	90	3	2.5	SEIDEL	88	IMB
> 1.5	p	90	0		[31] BARTELT	87	SOUD
> 40	p	90	7	6	HAINES	86	IMB
> 19	p	90	1	<1.1	ARISAKA	85	KAMI
> 6.7	p (free)	90	11	13	BLEWITT	85	IMB
> 40	p	90	7	8	BLEWITT	85	IMB
> 6	p	90	1		BATTISTONI	84	NUSX
> 0.6	p	90	0		[32] BARTELT	83	SOUD
> 0.4	n	90	0		[32] BARTELT	83	SOUD
> 5.8	p	90	2		[33] KRISHNA...	82	KOLR
> 2.0	p	90	0		CHERRY	81	HOME
> 0.2	n	90			[34] GURR	67	CNTR

[31] BARTELT 87 limit applies to $p \to \mu^+K^0_S$.
[32] Limit based on zero events.
[33] We have calculated 90% CL limit from 1 confined event.
[34] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+K^0_S)$ τ_{17}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>64	**p**	**90**	**0**	**1.2**	BERGER	91	FREJ

$\tau(p \to \mu^+K^0_L)$ τ_{18}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>44	**p**	**90**	**0**	**≤ 0.1**	BERGER	91	FREJ

$\tau(N \to \nu K)$ τ_{19}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	**p**	**90**	**9**	**7.3**	HIRATA	89C	KAMI
> 86	**n**	**90**	**0**	**2.4**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 15	n	90	1	1.8	BERGER	89	FREJ
> 15	p	90	1	1.8	BERGER	89	FREJ
> 0.28	p	90	0	0.7	PHILLIPS	89	HPW
> 0.3	p	90	0		BARTELT	87	SOUD
> 0.75	n	90	0		[35] BARTELT	87	SOUD
> 10	p	90	6	5	HAINES	86	IMB
> 15	n	90	3	5	HAINES	86	IMB
> 28	p	90	3	3	KAJITA	86	KAMI
> 32	n	90	0	1.4	KAJITA	86	KAMI
> 1.8	p (free)	90	6	11	BLEWITT	85	IMB
> 9.6	p	90	6	5	BLEWITT	85	IMB
> 10	n	90	2	2	PARK	85	IMB
> 5	n	90	0		BATTISTONI	84	NUSX
> 2	p	90	0		BATTISTONI	84	NUSX
> 0.3	n	90	0		[36] BARTELT	83	SOUD
> 0.1	p	90	0		[36] BARTELT	83	SOUD
> 5.8	p	90	1		[37] KRISHNA...	82	KOLR
> 0.3	n	90	2		[38] CHERRY	81	HOME

[35] BARTELT 87 limit applies to $n \to \nu K^0_S$.
[36] Limit based on zero events.
[37] We have calculated 90% CL limit from 1 confined event.
[38] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+K^*(892)^0)$ τ_{20}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>52	**p**	**90**	**2**	**1.55**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>10	p	90	0	0.8	BERGER	91	FREJ
>10	p	90	1	<1	ARISAKA	85	KAMI

$\tau(N \to \nu K^*(892))$ τ_{21}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>22	**n**	**90**	**0**	**2.1**	BERGER	89	FREJ
>20	**p**	**90**	**5**	**2.1**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

>17	*p*	90	0	2.4	BERGER	89	FREJ
>21	*n*	90	4	2.4	HIRATA	89C	KAMI
>10	*p*	90	7	6	HAINES	86	IMB
> 5	*n*	90	8	7	HAINES	86	IMB
> 8	*p*	90	3	2	KAJITA	86	KAMI
> 6	*n*	90	2	1.6	KAJITA	86	KAMI
> 5.8	*p* (free)	90	10	16	BLEWITT	85	IMB
> 9.6	*p*	90	7	6	BLEWITT	85	IMB
> 7	*n*	90	1	4	PARK	85	IMB
> 2.1	*p*	90	1		[39] BATTISTONI	82	NUSX

[39] We have converted 1 possible event to 90% CL limit.

$\tau(p \to e^+ \pi^+ \pi^-)$ T22

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>21	***p***	**90**	**0**	**2.2**	BERGER	91	FREJ

$\tau(p \to e^+ \pi^0 \pi^0)$ T23

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>38	***p***	**90**	**1**	**0.5**	BERGER	91	FREJ

$\tau(n \to e^+ \pi^- \pi^0)$ T24

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>32	***n***	**90**	**1**	**0.8**	BERGER	91	FREJ

$\tau(p \to \mu^+ \pi^+ \pi^-)$ T25

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>17	***p***	**90**	**1**	**2.6**	BERGER	91	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 3.3	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to \mu^+ \pi^0 \pi^0)$ T26

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>33	***p***	**90**	**1**	**0.9**	BERGER	91	FREJ

$\tau(n \to \mu^+ \pi^- \pi^0)$ T27

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>33	***n***	**90**	**0**	**1.1**	BERGER	91	FREJ

$\tau(n \to e^+ K^0 \pi^-)$ T28

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>18	***n***	**90**	**1**	**0.2**	BERGER	91	FREJ

$\tau(n \to e^- \pi^+)$ T29

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>65	***n***	**90**	**0**	**1.6**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>55	*n*	90	0	1.09	BERGER	91B	FREJ
>16	*n*	90	9	7	HAINES	86	IMB
>25	*n*	90	2	4	PARK	85	IMB

$\tau(n \to \mu^- \pi^+)$ T30

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>49	***n***	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>33	*n*	90	0	1.40	BERGER	91B	FREJ
> 2.7	*n*	90	0	0.7	PHILLIPS	89	HPW
>25	*n*	90	7	6	HAINES	86	IMB
>27	*n*	90	2	3	PARK	85	IMB

$\tau(n \to e^- \rho^+)$ T31

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>62	***n***	**90**	**2**	**4.1**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>12	*n*	90	13	6	HAINES	86	IMB
>12	*n*	90	5	3	PARK	85	IMB

$\tau(n \to \mu^- \rho^+)$ T32

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>7	***n***	**90**	**1**	**1.1**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>2.6	*n*	90	0	0.7	PHILLIPS	89	HPW
>9	*n*	90	7	5	HAINES	86	IMB
>9	*n*	90	2	2	PARK	85	IMB

$\tau(n \to e^- K^+)$ T33

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>32	***n***	**90**	**3**	**2.96**	BERGER	91B	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 0.23	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- K^+)$ T34

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	***n***	**90**	**0**	**2.18**	BERGER	91B	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 4.7	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^- \pi^+ \pi^+)$ T35

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>30	***p***	**90**	**1**	**2.50**	BERGER	91B	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 2.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to e^- \pi^+ \pi^0)$ T36

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>29	***n***	**90**	**1**	**0.78**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ \pi^+)$ T37

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>17	***p***	**90**	**1**	**1.72**	BERGER	91B	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 7.8	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- \pi^+ \pi^0)$ T38

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>34	***n***	**90**	**0**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^- \pi^+ K^+)$ T39

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>20	***p***	**90**	**3**	**2.50**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ K^+)$ T40

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>5	***p***	**90**	**2**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^+ \gamma)$ T41

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>460	***p***	**90**	**0**	**0.6**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>133	*p*	90	0	0.3	BERGER	91	FREJ
>360	*p*	90	0	0.3	HAINES	86	IMB
> 87	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>360	*p*	90	0	0.2	BLEWITT	85	IMB
> 0.1	*p*	90			[40] GURR	67	CNTR

[40] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+ \gamma)$ T42

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>380	***p***	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>155	*p*	90	0	0.1	BERGER	91	FREJ
> 97	*p*	90	3	2	HAINES	86	IMB
> 61	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>280	*p*	90	0	0.6	BLEWITT	85	IMB
> 0.3	*p*	90			[41] GURR	67	CNTR

[41] We have converted half-life to 90% CL mean life.

$\tau(n \to \nu \gamma)$ T43

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>24	***n***	**90**	**10**	**6.86**	BERGER	91B	FREJ

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 9	*n*	90	73	60	HAINES	86	IMB
>11	*n*	90	28	19	PARK	85	IMB

$\tau(p \to e^+ \gamma \gamma)$ T44

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	***p***	**90**	**1**	**0.8**	BERGER	91	FREJ

$\tau(p \to e^+e^+e^-)$ T45

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>510	***p***	**90**	**0**	**0.3**	HAINES 86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>147	*p*	90	0	0.1	BERGER 91	FREJ
> 89	*p* (free)	90	0	0.5	BLEWITT 85	IMB
>510	*p*	90	0	0.7	BLEWITT 85	IMB

$\tau(p \to e^+\mu^+\mu^-)$ T46

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>81	***p***	**90**	**0**	**0.16**	BERGER 91	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 5.0	*p*	90	0	0.7	PHILLIPS 89	HPW

$\tau(p \to e^+\nu\nu)$ T47

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>11	***p***	**90**	**11**	**6.08**	BERGER 91B	FREJ

$\tau(n \to e^+e^-\nu)$ T48

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>74	***n***	**90**	**0**	**< 0.1**	BERGER 91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>45	*n*	90	5	5	HAINES 86	IMB
>26	*n*	90	4	3	PARK 85	IMB

$\tau(n \to \mu^+e^-\nu)$ T49

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>47	***n***	**90**	**0**	**< 0.1**	BERGER 91B	FREJ

$\tau(n \to \mu^+\mu^-\nu)$ T50

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>42	***n***	**90**	**0**	**1.4**	BERGER 91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 5.1	*n*	90	0	0.7	PHILLIPS 89	HPW
>16	*n*	90	14	7	HAINES 86	IMB
>19	*n*	90	4	7	PARK 85	IMB

$\tau(p \to \mu^+e^+e^-)$ T51

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>91	***p***	**90**	**0**	**≤ 0.1**	BERGER 91	FREJ

$\tau(p \to \mu^+\mu^+\mu^-)$ T52

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>190	***p***	**90**	**1**	**0.1**	HAINES 86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>119	*p*	90	0	0.2	BERGER 91	FREJ
> 10.5	*p*	90	0	0.7	PHILLIPS 89	HPW
> 44	*p* (free)	90	1	0.7	BLEWITT 85	IMB
>190	*p*	90	1	0.9	BLEWITT 85	IMB
> 2.1	*p*	90	1		[42] BATTISTONI 82	NUSX

[42] We have converted 1 possible event to 90% CL limit.

$\tau(p \to \mu^+\nu\nu)$ T53

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>21	***p***	**90**	**7**	**11.23**	BERGER 91B	FREJ

$\tau(p \to e^-\mu^+\mu^+)$ T54

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>6.0	***p***	**90**	**0**	**0.7**	PHILLIPS 89	HPW

$\tau(n \to 3\nu)$ T55

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.00049	***n***	**90**	**2**	**2**	[43] SUZUKI 93B	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.0023	*n*	90			[44] GLICENSTEIN 97	KAMI
>0.00003	*n*	90	11	6.1	[45] BERGER 91B	FREJ
>0.00012	*n*	90	7	11.2	[45] BERGER 91B	FREJ
>0.0005	*n*	90	0		LEARNED 79	RVUE

[43] The SUZUKI 93B limit applies to any of $\nu_e\nu_e\overline{\nu}_e$, $\nu_\mu\nu_\mu\overline{\nu}_\mu$, or $\nu_\tau\nu_\tau\overline{\nu}_\tau$.

[44] GLICENSTEIN 97 uses Kamioka data and the idea that the disappearance of the neutron's magnetic moment should produce radiation.

[45] The first BERGER 91B limit is for $n \to \nu_e\nu_e\overline{\nu}_e$, the second is for $n \to \nu_\mu\nu_\mu\overline{\nu}_\mu$.

$\tau(n \to 5\nu)$ T56

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.0017	*n*	90			[46] GLICENSTEIN 97	KAMI

[46] GLICENSTEIN 97 uses Kamioka data and the idea that the disappearance of the neutron's magnetic moment should produce radiation.

$\tau(N \to e^+\text{anything})$ T57

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.6	***p, n***	**90**			[47] LEARNED 79	RVUE

[47] The electron may be primary or secondary.

$\tau(N \to \mu^+\text{anything})$ T58

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>12	***p, n***	**90**	**2**		[48,49] CHERRY 81	HOME
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 1.8	*p, n*	90			[49] COWSIK 80	CNTR
> 6	*p, n*	90			[49] LEARNED 79	RVUE

[48] We have converted 2 possible events to 90% CL limit.

[49] The muon may be primary or secondary.

$\tau(N \to \nu\text{anything})$ T59

Anything = π, ρ, K, etc.

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.0002	*p, n*	90	0		LEARNED 79	RVUE

$\tau(N \to e^+\pi^0\text{anything})$ T60

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.6	***p, n***	**90**	**0**		LEARNED 79	RVUE

$\tau(N \to 2\text{ bodies}, \nu\text{-free})$ T61

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.3	*p, n*	90	0		ALEKSEEV 81	BAKS

$\tau(pp \to \pi^+\pi^+)$ T62

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.7	**90**	**4**	**2.34**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to \pi^+\pi^0)$ T63

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>2.0	**90**	**0**	**0.31**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^+\pi^-)$ T64

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.7	**90**	**4**	**2.18**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^0\pi^0)$ T65

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>3.4	**90**	**0**	**0.78**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+e^+)$ T66

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>5.8	**90**	**0**	**<0.1**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+\mu^+)$ T67

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>3.6	**90**	**0**	**<0.1**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to \mu^+\mu^+)$ T68

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>1.7	**90**	**0**	**0.62**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to e^+\overline{\nu})$ T69

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>2.8	**90**	**5**	**9.67**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to \mu^+\overline{\nu})$ T70

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>1.6	**90**	**4**	**4.37**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \rightarrow \nu_e \overline{\nu}_e)$ τ_{71}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.000012	**90**	**5**	**9.7**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \rightarrow \nu_\mu \overline{\nu}_\mu)$ τ_{72}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.000006	**90**	**4**	**4.4**	BERGER 91B	FREJ	τ per iron nucleus

$\overline{p}$ PARTIAL MEAN LIVES

The "partial mean life" limits tabulated here are the limits on $\overline{\tau}/B_j$, where $\overline{\tau}$ is the total mean life for the antiproton and B_j is the branching fraction for the mode in question.

$\tau(\overline{p} \rightarrow e^- \gamma)$ τ_{73}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>1848	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \rightarrow e^- \pi^0)$ τ_{74}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>554	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \rightarrow e^- \eta)$ τ_{75}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>171	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \rightarrow e^- K^0_S)$ τ_{76}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>29	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \rightarrow e^- K^0_L)$ τ_{77}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>9	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

p REFERENCES

GLICENSTEIN	97	PL B411 326	J.F. Glicenstein	(SACL)
GABRIELSE	95	PRL 74 3544	+Phillips, Quint+	(HARV, MANZ, SEOUL)
MACGIBBON	95	PR C52 2097	+Garino, Lucas, Nathan+	(ILL, SASK, INRM)
GEER	94	PRL 72 1596	+Marriner, Ray+	(FNAL, UCLA, PSU)
HALLIN	93	PR C48 1497	+Amendt, Bergstrom+	(SASK, BOST, ILL)
SUZUKI	93B	PL B311 357	+Fukuda, Hirata, Inoue+	(KAMIOKANDE Collab.)
HUGHES	92	PRL 69 578	+Deutch	(LANL, AARH)
ZIEGER	92	PL B278 34	+Van de Vyver, Christmann, DeGraeve+	(MPCM)
Also	92B	PL B281 417 (erratum)	Zieger, ..., Van den Abeele, Ziegler	(MPCM)
BERGER	91	ZPHY C50 385	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
BERGER	91B	PL B269 227	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
FEDERSPIEL	91	PRL 67 1511	+Eisenstein, Lucas, MacGibbon+	(ILL)
BECKER-SZ...	90	PR D42 2974	Becker-Szendy, Bratton, Cady, Casper+	(IMB-3 Collab.)
ERICSON	90	EPL 11 295	+Richter	(CERN, DARM)
GABRIELSE	90	PRL 65 1317	+Fei, Orozco, Tjoelker+	(HARV, MANZ, WASH, IBS)
BERGER	89	NP B313 509	+Froehlich, Moench+	(FREJUS Collab.)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
HIRATA	89C	PL B220 308	+Kajita, Kifune, Kihara+	(Kamiokande Collab.)
PHILLIPS	89	PL B224 348	+Matthews, Aprile, Cline+	(HPW Collab.)
KREISSL	88	ZPHY C37 557	+Hancock, Koch, Koehler, Poth+	(CERN PS176 Collab.)
SEIDEL	88	PRL 61 2522	+Bionta, Blewitt, Bratton+	(IMB Collab.)
BARTELT	87	PR D36 1990	+Courant, Heller+	(Soudan Collab.)
Also	89	PR D40 1701 erratum	Bartelt, Courant, Heller+	(Soudan Collab.)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
HAINES	86	PRL 57 1986	+Bionta, Blewitt, Bratton, Casper+	(IMB Collab.)
KAJITA	86	JPSJ 55 711	+Arisaka, Koshiba, Nakahata+	(Kamiokande Collab.)
ARISAKA	85	JPSJ 54 3213	+Kajita, Koshiba, Nakahata+	(Kamiokande Collab.)
BLEWITT	85	PRL 55 2114	+LoSecco, Bionta, Bratton+	(IMB Collab.)
DZUBA	85	PL 154B 93	+Flambaum, Silvestrov	(NOVO)
PARK	85	PRL 54 22	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WILKENING	84	PR A29 425	+Ramsey, Larson	(HARV, VIRG)
BARTELT	83	PRL 50 651	+Courant, Heller, Joyce, Marshak+	(MINN, ANL)
BATTISTONI	82	PL 118B 461	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
KRISHNA...	82	PL 115B 349	Krishnaswamy, Menon+	(TATA, OSKC, INUS)
ALEKSEEV	81	JETPL 33 651 Translated from ZETFP 33 664.	+Bakatanov, Butkevich, Voevodskii+	(PNPI)
CHERRY	81	PRL 47 1507	+Deakyne, Lande, Lee, Steinberg+	(PENN, BNL)
COWSIK	80	PR D22 2204	+Narasimhan	(TATA)
BELL	79	PL 86B 215	+Calvetti, Carron, Chaney, Cittolin+	(CERN)
GOLDEN	79	PRL 43 1196	+Horan, Mauger, Badhwar, Lacy+	(NASA, PSLL)
LEARNED	79	PRL 43 907	+Reines, Soni	(UCI)
BREGMAN	78	PL 78B 174	+Calvetti, Carron, Cittolin, Hauer, Herr+	(CERN)
ROBERTS	78	PR D17 358		(WILL, RHEL)
EVANS	77	Science 197 989	+Steinberg	(BNL, PENN)
ROBERSON	77	PR C16 1945	+King, Kunselman+	(WYOM, CIT, CMU, VPI, WILL)
HU	75	NP A254 403	+Asano, Chen, Cheng, Dugan+	(COLU, YALE)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DYLLA	73	PR A7 1224	+King	(MIT)
BAMBERGER	70	PL 33B 233	+Lynen, Piekarz+	(MPIH, CERN, KARL)
DIX	70	Thesis Case		(CASE)
HARRISON	69	PRL 22 1263	+Sandars, Wright	(OXF)
GURR	67	PR 158 1321	+Kropp, Reines, Meyer	(CASE, WITW)
FLEROV	58	DOKL 3 79	+Klochkov, Skobkin, Terentev	(ASCI)

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

n MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnotes. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge. The DIFILIPPO 94 value, in u, is by far the best, but when converted to MeV differs only negligibly from the 1986 CODATA value, which, for consistency, we stick with.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
939.56563±0.00028	[1] COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
939.56565±0.00028	[2,3] DIFILIPPO 94	TRAP	Penning trap
939.56564±0.00028	[3,4] GREENE 86	SPEC	$np \rightarrow d\gamma$
939.5731 ±0.0027	[3] COHEN 73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.008664904 \pm 0.000000014$ u.

[2] The mass is known much more precisely in u: $m = 1.0086649235 \pm 0.0000000023$ u. We use the conversion factor given above to get the mass in MeV.

[3] These determinations are not independent of the $m_n - m_p$ measurements below.

[4] The mass is known much more precisely in u: $m = 1.008664919 \pm 0.000000014$ u.

$\overline{n}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
939.485±0.051	59	[5] CRESTI 86	HBC	$\overline{p}p \rightarrow \overline{n}n$

[5] This is a corrected result (see the erratum). The error is statistical. The maximum systematic error is 0.029 MeV.

$(m_n - m_{\overline{n}})$ / m_{average}

A test of *CPT* invariance. Calculated from the *n* and $\overline{n}$ masses, above.

VALUE	DOCUMENT ID
(9±5) × 10^{-5} OUR EVALUATION	

$m_n - m_p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1.293318 ±0.000009	[6] COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.2933328±0.0000072	GREENE 86	SPEC	$np \rightarrow d\gamma$
1.293429 ±0.000036	COHEN 73	RVUE	1973 CODATA value

[6] Calculated by us from the COHEN 87 ratio $m_n/m_p = 1.001378404 \pm 0.000000009$. In u, $m_n - m_p = 0.001388434 \pm 0.000000009$ u.

n MEAN LIFE

We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. (Limits on lifetimes for *bound* neutrons are given in the section "*p* PARTIAL MEAN LIVES.")

For a review, see EROZOLIMSKII 89 and papers that follow it in an issue of NIM devoted to the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989). For later reviews and/or commentary, see FREEDMAN 90, SCHRECKENBACH 92, and PENDLEBURY 93.

VALUE (s)	DOCUMENT ID	TECN	COMMENT
886.7± 1.9 OUR AVERAGE	Error includes scale factor of 1.2.		
889.2± 3.0± 3.8	BYRNE 96	CNTR	Penning trap
882.6± 2.7	[7] MAMPE 93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV... 92	CNTR	Gravitational trap
878 ±27 ±14	KOSSAKOW... 89	TPC	Pulsed beam
887.6± 3.0	MAMPE 89	CNTR	Gravitational trap
877 ±10	PAUL 89	CNTR	Storage ring
876 ±10 ±19	LAST 88	SPEC	Pulsed beam
891 ± 9	SPIVAK 88	CNTR	Beam
903 ±13	KOSVINTSEV 86	CNTR	Gravitational trap
918 ±14	CHRISTENSEN 72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
888.4± 2.9	ALFIMENKOV 90	CNTR	See NESVIZHEVSKII 92
893.6± 3.8± 3.7	BYRNE 90	CNTR	See BYRNE 96
937 ±18	[8] BYRNE 80	CNTR	
875 ±95	KOSVINTSEV 80	CNTR	
881 ± 8	BONDAREN... 78	CNTR	See SPIVAK 88

[7] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.

[8] This measurement has been withdrawn (J. Byrne, private communication, 1990).

n MAGNETIC MOMENT

VALUE (μ_N)	DOCUMENT ID	TECN	COMMENT
−1.91304275±0.00000045	COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−1.91304277±0.00000048	[9] GREENE 82	MRS	

[9] GREENE 82 measures the moment to be $(1.04187564 \pm 0.00000026) \times 10^{-3}$ Bohr magnetons. The value above is obtained by multiplying this by $m_p/m_e = 1836.152701 \pm 0.000037$ (the 1986 CODATA value from COHEN 87).

n ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance. A number of early results have been omitted. See RAMSEY 90 and GOLUB 94 for reviews.

VALUE (10^{-25} *e*cm)	CL%	DOCUMENT ID	TECN	COMMENT
< 0.97	90	ALTAREV 96	MRS	$(+0.26 \pm 0.40 \pm 0.16) \times 10^{-25}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 1.1	95	ALTAREV 92	MRS	See ALTAREV 96
< 1.2	95	SMITH 90	MRS	$d = (-0.3 \pm 0.5) \times 10^{-25}$
< 2.6	95	ALTAREV 86	MRS	$d = (-1.4 \pm 0.6) \times 10^{-25}$
0.3 ±4.8		PENDLEBURY 84	MRS	Ultracold neutrons
< 6	90	ALTAREV 81	MRS	$d = (2.1 \pm 2.4) \times 10^{-25}$
<16	90	ALTAREV 79	MRS	$d = (4.0 \pm 7.5) \times 10^{-25}$

n ELECTRIC POLARIZABILITY α_n

Following is the electric polarizability α_n defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_n\mathbf{E}$. For a review, see SCHMIEDMAYER 89.

VALUE (10^{-3} fm^3)	DOCUMENT ID	TECN	COMMENT
$0.98^{+0.19}_{-0.23}$ OUR AVERAGE	Error includes scale factor of 1.1.		
0.0 ±0.5	[10] KOESTER 95	CNTR	*n* Pb, *n* Bi transmission
1.20±0.15±0.20	SCHMIEDM... 91	CNTR	*n* Pb transmission
$1.07^{+0.33}_{-1.07}$	ROSE 90B	CNTR	$\gamma d \rightarrow \gamma n p$
0.8 ±1.0	KOESTER 88	CNTR	*n* Pb, *n* Bi transmission
1.2 ±1.0	SCHMIEDM... 88	CNTR	*n* Pb, *n* C transmission
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.17^{+0.43}_{-1.17}$	ROSE 90	CNTR	See ROSE 90B

[10] KOESTER 95 uses natural Pb and the isotopes 208, 207, and 206. See this paper for a discussion of methods used by various groups to extract α_n from data.

n CHARGE

See also "$|q_p + q_e|/e$" in the proton Listings.

VALUE (10^{-21} *e*)	DOCUMENT ID	TECN	COMMENT
− 0.4± 1.1	[11] BAUMANN 88		Cold *n* deflection
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−15 ±22	[12] GAEHLER 82	CNTR	Reactor neutrons

[11] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.

[12] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

LIMIT ON $n\overline{n}$ OSCILLATIONS

Mean Time for $n\overline{n}$ Transition in Vacuum

A test of ΔB=2 baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, and ALBERICO 91 for discussions. Direct searches for $n \rightarrow \overline{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	CL%	DOCUMENT ID	TECN	COMMENT
$>1.2 \times 10^8$	90	BERGER 90	FREJ	*n* bound in iron
$>1.2 \times 10^8$	90	TAKITA 86	CNTR	Kamiokande
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>8.6 \times 10^7$	90	BALDO-... 94	CNTR	Reactor neutrons
$>1 \times 10^7$	90	BALDO-... 90	CNTR	See BALDO-CEOLIN 94
$>4.9 \times 10^5$	90	BRESSI 90	CNTR	Reactor neutrons
$>4.7 \times 10^5$	90	BRESSI 89	CNTR	See BRESSI 90
$>1 \times 10^6$	90	FIDECARO 85	CNTR	Reactor neutrons
$>8.8 \times 10^7$	90	PARK 85B	CNTR	
$>3 \times 10^7$		BATTISTONI 84	NUSX	
$> 2.7 \times 10^7$–1.1×10^8		JONES 84	CNTR	
$>2 \times 10^7$		CHERRY 83	CNTR	

n DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$pe^-\overline{\nu}_e$	100 %	
Γ_2	hydrogen-atom $\overline{\nu}_e$		
	Charge conservation (*Q*) violating mode		
Γ_3	$p\nu_e\overline{\nu}_e$	*Q* $< 8 \times 10^{-27}$	68%

n BRANCHING RATIOS

$\Gamma(\text{hydrogen-atom}\,\overline{\nu}_e)/\Gamma_{\text{total}}$ **Γ_2/Γ**

VALUE	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<3 \times 10^{-2}$	95	[13] GREEN 90	RVUE

[13] GREEN 90 infers that $\tau(\text{hydrogen-atom}\,\overline{\nu}_e) > 3 \times 10^4$ s by comparing neutron lifetime measurements made in storage experiments with those made in β-decay experiments. However, the result depends sensitively on the lifetime measurements, and does not of course take into account more recent measurements of same.

$\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$ **Γ_3/Γ**

Forbidden by charge conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8 \times 10^{-27}$	68	[14] NORMAN 96	RVUE	^{71}Ga → ^{71}Ge neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<9.7 \times 10^{-18}$	90	ROY 83	CNTR	^{113}Cd → ^{113m}In neut.
$<7.9 \times 10^{-21}$		VAIDYA 83	CNTR	^{87}Rb → ^{87m}Sr neut.
$<9 \times 10^{-24}$	90	BARABANOV 80	CNTR	^{71}Ga → ^{71}GeX
$<3 \times 10^{-19}$		NORMAN 79	CNTR	^{87}Rb → ^{87m}Sr neut.

[14] NORMAN 96 gets this limit by attributing SAGE and GALLEX counting rates to the charge-nonconserving transition $^{71}\text{Ga} \rightarrow {}^{71}\text{Ge}$+neutrals rather than to solar-neutrino reactions.

NOTE ON BARYON DECAY PARAMETERS

Written 1996 by E.D. Commins (University of California, Berkeley).

Baryon semileptonic decays

The typical spin-1/2 baryon semileptonic decay is described by a matrix element, the hadronic part of which may be written as:

$$\overline{B}_f\left[f_1(q^2)\gamma_\lambda + i\,f_2(q^2)\sigma_{\lambda\mu}q^\mu + g_1(q^2)\gamma_\lambda\gamma_5 + g_3(q^2)\gamma_5 q_\lambda\right]B_i\ .$$

Here B_i and $\overline{B}_f$ are spinors describing the initial and final baryons, and $q = p_i - p_f$, while the terms in f_1, f_2, g_1, and g_3 account for vector, induced tensor ("weak magnetism"), axial vector, and induced pseudoscalar contributions [1]. Second-class current contributions are ignored here. In the limit of zero momentum transfer, f_1 reduces to the vector coupling constant g_V, and g_1 reduces to the axial-vector coupling constant g_A. The latter coefficients are related by Cabibbo's theory [2], generalized to six quarks (and three mixing angles) by Kobayashi and Maskawa [3]. The g_3 term is negligible for transitions in which an $e^\pm$ is emitted, and gives a very small correction, which can be estimated by PCAC [4], for $\mu^\pm$ modes. Recoil effects include weak magnetism, and are taken into account adequately by considering terms of first order in

$$\delta = \frac{m_i - m_f}{m_i + m_f}\ ,$$

where m_i and m_f are the masses of the initial and final baryons.

The experimental quantities of interest are the total decay rate, the lepton-neutrino angular correlation, the asymmetry coefficients in the decay of a polarized initial baryon, and the polarization of the decay baryon in its own rest frame for an unpolarized initial baryon. Formulae for these quantities are derived by standard means [5] and are analogous to formulae for nuclear beta decay [6]. We use the notation of Ref. 6 in the Listings for neutron beta decay. For comparison with experiments at higher q^2, it is necessary to modify the form factors at $q^2 = 0$ by a "dipole" q^2 dependence, and for high-precision comparisons to apply appropriate radiative corrections [7].

The ratio g_A/g_V may be written as

$$g_A/g_V = |\, g_A/g_V \,|\, e^{i\phi_{AV}} .$$

The presence of a "triple correlation" term in the transition probability, proportional to $\mathrm{Im}(g_A/g_V)$ and of the form

$$\sigma_i \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for initial baryon polarization or

$$\sigma_f \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for final baryon polarization, would indicate failure of time-reversal invariance. The phase angle ϕ has been measured precisely only in neutron decay (and in ^{19}Ne nuclear beta decay), and the results are consistent with T invariance.

Hyperon nonleptonic decays

The amplitude for a spin-1/2 hyperon decaying into a spin-1/2 baryon and a spin-0 meson may be written in the form

$$M = G_F m_\pi^2 \cdot \overline{B}_f (A - B\gamma_5) B_i ,$$

where A and B are constants [1]. The transition rate is proportional to

$$R = 1 + \gamma \widehat{\omega}_f \cdot \widehat{\omega}_i + (1-\gamma)(\widehat{\omega}_f \cdot \widehat{\mathbf{n}})(\widehat{\omega}_i \cdot \widehat{\mathbf{n}})$$
$$+ \alpha(\widehat{\omega}_f \cdot \widehat{\mathbf{n}} + \widehat{\omega}_i \cdot \widehat{\mathbf{n}}) + \beta \widehat{\mathbf{n}} \cdot (\widehat{\omega}_f \times \widehat{\omega}_i) ,$$

where $\widehat{\mathbf{n}}$ is a unit vector in the direction of the final baryon momentum, and $\widehat{\omega}_i$ and $\widehat{\omega}_f$ are unit vectors in the directions of the initial and final baryon spins. (The sign of the last term in the above equation was incorrect in our 1988 and 1990 editions.) The parameters α, β, and γ are defined as

$$\alpha = 2\,\mathrm{Re}(s^* p)/(\,|s|^2 + |p|^2) ,$$
$$\beta = 2\,\mathrm{Im}(s^* p)/(\,|s|^2 + |p|^2) ,$$
$$\gamma = (\,|s|^2 - |p|^2)/(\,|s|^2 + |p|^2) ,$$

where $s = A$ and $p = |\mathbf{p}_f|\, B/(E_f + m_f)$; here E_f and $\mathbf{p}_f$ are the energy and momentum of the final baryon. The parameters α, β, and γ satisfy

$$\alpha^2 + \beta^2 + \gamma^2 = 1 .$$

If the hyperon polarization is $\mathbf{P}_Y$, the polarization $\mathbf{P}_B$ of the decay baryons is

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \widehat{\mathbf{n}})\widehat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \widehat{\mathbf{n}}) + \gamma \widehat{\mathbf{n}} \times (\mathbf{P}_Y \times \widehat{\mathbf{n}})}{1 + \alpha \mathbf{P}_Y \cdot \widehat{\mathbf{n}}} .$$

Here $\mathbf{P}_B$ is defined in the rest system of the baryon, obtained by a Lorentz transformation along $\widehat{\mathbf{n}}$ from the hyperon rest frame, in which $\widehat{\mathbf{n}}$ and $\mathbf{P}_Y$ are defined.

An additional useful parameter ϕ is defined by

$$\beta = (1 - \alpha^2)^{1/2} \sin\phi .$$

In the Listings, we compile α and ϕ for each decay, since these quantities are most closely related to experiment and are essentially uncorrelated. When necessary, we have changed the signs of reported values to agree with our sign conventions. In the Baryon Summary Table, we give α, ϕ, and Δ (defined below) with errors, and also give the value of γ without error.

Time-reversal invariance requires, in the absence of final-state interactions, that s and p be relatively real, and therefore that $\beta = 0$. However, for the decays discussed here, the final-state interaction is strong. Thus

$$s = |s|\, e^{i\delta_s} \text{ and } p = |p|\, e^{i\delta_p} ,$$

where δ_s and δ_p are the pion-baryon s- and p-wave strong interaction phase shifts. We then have

$$\beta = \frac{-2\,|s|\,|p|}{|s|^2 + |p|^2} \sin(\delta_s - \delta_p) .$$

One also defines $\Delta = -\tan^{-1}(\beta/\alpha)$. If T invariance holds, $\Delta = \delta_s - \delta_p$. For $\Lambda \rightarrow p\pi^-$ decay, the value of Δ may be compared with the s- and p-wave phase shifts in low-energy $\pi^- p$ scattering, and the results are consistent with T invariance.

Radiative hyperon decays

For the radiative decay of a polarized spin-1/2 hyperon, $B_i \rightarrow B_f \gamma$, the angular distribution of the direction $\widehat{p}$ of the final spin-1/2 baryon in the hyperon rest frame is

$$\frac{d\Gamma_\gamma}{d\Omega} = \frac{\Gamma_\gamma}{4\pi}(1 + \alpha_\gamma \widehat{p} \cdot \mathbf{P}_i) ,$$

where $\mathbf{P}_i$ is the hyperon polarization and the asymmetry parameter α_γ is

$$\alpha_\gamma = \frac{2\mathrm{Re}\left[g_1'(0) f_M^*(0)\right]}{|g_1'(0)|^2 + |f_M(0)|^2} .$$

Here $f_M = \dfrac{(m_i - m_f)}{(m_i + m_f)} \left[(m_i + m_f) f_2' - f_1'\right]$, where $f_1'(q^2)$, $f_2'(q^2)$, and $g_1'(q^2)$ are the $\Delta Q = 0$ analogs of the $|\Delta Q| = 1$ form factors defined above.

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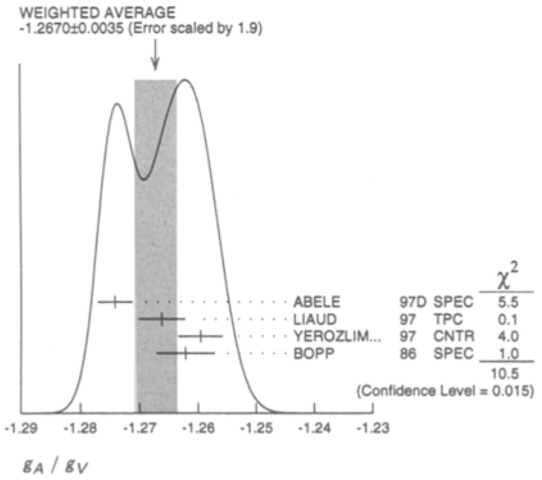
$n \rightarrow pe^- \nu$ DECAY PARAMETERS

See the above "Note on Baryon Decay Parameters." For discussions of recent results, see the references cited at the beginning of the section on the neutron mean life. For discussions of the values of the weak coupling constants g_A and g_V obtained using the neutron lifetime and asymmetry parameter *A*, comparisons with other methods of obtaining these constants, and implications for particle physics and for astrophysics, see DUBBERS 91 and WOOLCOCK 91. For tests of the *V−A* theory of neutron decay, see EROZOLIMSKII 91B and MOSTOVOI 96.

g_A / g_V

VALUE		*DOCUMENT ID*		*TECN*	*COMMENT*
−1.2670±0.0035 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.			
−1.274 ±0.003		ABELE	97D	SPEC	cold *n*, polarized
−1.266 ±0.004		LIAUD	97	TPC	*e* mom-*n* spin corr.
−1.2594±0.0038	15	YEROZLIM...	97	CNTR	*e* mom-*n* spin corr.
−1.262 ±0.005		BOPP	86	SPEC	*e* mom-*n* spin corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−1.266 ±0.004		SCHRECK...	95	TPC	See LIAUD 97
−1.2544±0.0036		EROZOLIM...	91	CNTR	See YEROZOLIMSKY 97
−1.226 ±0.042		MOSTOVOY	83	RVUE	
−1.261 ±0.012	16	EROZOLIM...	79	CNTR	*e* mom-*n* spin corr.
−1.259 ±0.017	16	STRATOWA	78	CNTR	proton recoil spectrum
−1.263 ±0.015		EROZOLIM...	77	CNTR	See EROZOLIMSKII 79
−1.250 ±0.036	16	DOBROZE...	75	CNTR	See STRATOWA 78
−1.258 ±0.015	17	KROHN	75	CNTR	*e* mom-*n* spin corr.
−1.263 ±0.016	18	KROPF	74	RVUE	*n* decay alone
−1.250 ±0.009	18	KROPF	74	RVUE	*n* decay + nuclear ft

[15] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
[16] These experiments measure the absolute value of g_A/g_V only.
[17] KROHN 75 includes events of CHRISTENSEN 70.
[18] KROPF 74 reviews all data through 1972.

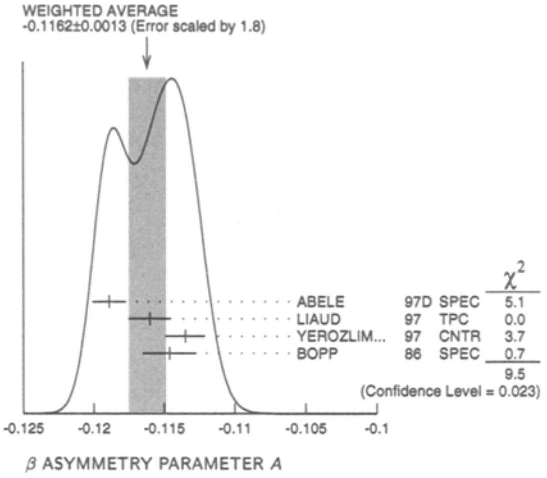


β ASYMMETRY PARAMETER *A*

This is the neutron-spin electron-momentum correlation coefficient. Unless otherwise noted, the values are corrected for radiative effects and weak magnetism.

VALUE		*DOCUMENT ID*		*TECN*	*COMMENT*
−0.1162±0.0013 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			
−0.1189±0.0012		ABELE	97D	SPEC	cold *n*, polarized
−0.1160±0.0009±0.0012		LIAUD	97	TPC	*e* mom-*n* spin corr.
−0.1135±0.0014	19	YEROZLIM...	97	CNTR	*e* mom-*n* spin corr.
−0.1146±0.0019		BOPP	86	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.1160±0.0009±0.0011		SCHRECK...	95	TPC	See LIAUD 97
−0.1116±0.0014		EROZOLIM...	91	CNTR	See YEROZOLIMSKY 97
−0.114 ±0.005	20	EROZOLIM...	79	CNTR	
−0.113 ±0.006	20	KROHN	75	CNTR	

[19] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
[20] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.



$\bar{\nu}$ ASYMMETRY PARAMETER *B*

This is the neutron-spin antineutrino-momentum correlation coefficient.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.990 ±0.008 OUR AVERAGE				
0.9894±0.0083	KUZNETSOV	95	CNTR	Cold polarized neutrons
0.995 ±0.034	CHRISTENSEN	70	CNTR	
1.00 ±0.05	EROZOLIM...	70C	CNTR	

e-$\bar{\nu}$ ANGULAR CORRELATION COEFFICIENT *a*

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.102 ±0.005 OUR AVERAGE				
−0.1017±0.0051	STRATOWA	78	CNTR	Proton recoil spectrum
−0.091 ±0.039	GRIGOREV	68	SPEC	Proton recoil spectrum

ϕ_{AV}, PHASE OF g_A RELATIVE TO g_V

Time reversal invariance requires this to be 0 or 180°.

VALUE (°)		*DOCUMENT ID*		*TECN*	*COMMENT*
180.07±0.18 OUR EVALUATION		Using the average value for quantity *D* given in the next data block and $\lambda \equiv g_A/g_V$ in $\sin\phi_{AV} = D(1+3\lambda^2)/2\lambda$.			
180.09±0.18 OUR AVERAGE					
179.71±0.39		EROZOLIM...	78	CNTR	Polarized neutrons
180.35±0.43		EROZOLIM...	74	CNTR	Polarized neutrons
180.14±0.22		STEINBERG	74	CNTR	Polarized neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
181.1 ±1.3	21	KROPF	74	RVUE	*n* decay

[21] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT *D*

These are measurements of the component of *n* spin perpendicular to the decay plane in β decay. Should be zero if *T* invariance is not violated.

VALUE		*DOCUMENT ID*		*TECN*	*COMMENT*
(−0.5 ±1.4) × 10^{-3} OUR AVERAGE					
+ 0.0022±0.0030		EROZOLIM...	78	CNTR	Polarized neutrons
− 0.0027±0.0050	22	EROZOLIM...	74	CNTR	Polarized neutrons
− 0.0011±0.0017		STEINBERG	74	CNTR	Polarized neutrons

[22] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 0.003, thus increasing the EROZOLIMSKII 74 error to 0.005. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

n REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

ABELE 97D PL B407 212 H. Abele+ (HEIDP, ILLG)
LIAUD 97 NP A612 53 +Schreckenbach, Kossakowski+ (ILLG, LAPP)
YEROZLIM... 97 PL B412 240 Yerozolimsky, Kuznetsov, Mostovoy+ (HARV, PNPI, KIAE)
ALTAREV 96 PAN 59 1152 +Borisov, Borovikova+ (PNPI)
Translated from YAF 59 1204.
BONDAREN... 96 JETPL 64 416 Bondarenko, Morozov, Panin, Fomin+ (KIAE)
Translated from ZETFP 64 382.
BYRNE 96 EPL 33 187 +Dawber, Habeck, Smidt+ (SUSS, ILLG)
MOSTOVOI 96 PAN 59 968 (KIAE)
Translated from YAF 59 1013.
NORMAN 96 PR D53 4086 +Bahcall, Goldhaber (LBL, IAS, BNL)
IGNATOVICH 95 JETPL 62 1 (JINR)
Translated from ZETFP 62 3.
KOESTER 95 PR C51 3363 +Waschkowski, Mitsyna+ (MUNT, JINR, LATV)
KUZNETSOV 95 PRL 75 794 +Serebrov, Stepanenko+ (PNPI, KIAE, HARV, NIST)
SCHRECK... 95 PL B349 427 Schreckenbach, Liaud+ (MUNT, ILLG, LAPP)
BALDO-... 94 ZPHY C63 409 Baldo-Ceolin, Benetti+ (HEID, ILLG, PADO, PAVI)
DIFILIPPO 94 PRL 73 1481 +Natarajan, Boyce, Pritchard (MIT)
Also 93 PRL 71 1998 Natarajan, Boyce, DiFilippo, Pritchard (MIT)
GOLUB 94 PRPL 237C 1 +Lamoreaux (HAHN, WASH)
MAMPE 93 JETPL 57 82 +Bondarenko, Morozov+ (KIAE)
Translated from ZETFP 57 77.
PENDLEBURY 93 ARNPS 43 687 (ILLG)
ALTAREV 92 PL B276 242 +Borisov, Borovikova, Ivanov+ (PNPI)
NESVIZHEV... 92 JETP 75 405 Nesvizhevskii, Serebrov, Tal'daev+ (PNPI, JINR)
Translated from ZETF 102 740.

SCHRECK...	92	JPG 18 1	Schreckenbach, Mampe	(ILLG)
ALBERICO	91	NP A523 488	+de Pace, Pignone	(TORI)
DUBBERS	91	NP A527 239c		(ILLG)
Also	90	EPL 11 195	Dubbers, Mampe, Doehner	(ILLG, HEID)
EROZOLIM...	91	PL B263 33	Erozolimskii, Kuznetsov, Stepanenko, Kuida+	(PNPI, KIAE)
Also	90	SJNP 52 999 Translated from YAF 52 1583.	Erozolimskii, Kuznetsov, Stepanenko, Kuida+	(PNPI, KIAE)
EROZOLIM...	91B	SJNP 53 260 Translated from YAF 53 418.	Erozolimskii, Mostovoi	(KIAE)
SCHMIEDM...	91	PRL 66 1015	Schmiedmayer, Riehs, Harvey, Hill	(TUW, ORNL)
WOOLCOCK	91	MPL A6 2579		(CANB)
ALFIMENKOV	90	JETPL 52 373 Translated from ZETFP 52 984.	+Varlamov, Vasil'ev, Gudkov+	(PNPI, JINR)
BALDO-...	90	PL B236 95	Baldo-Ceolin, Benetti, Bitter+	(PADO, PAVI, HEIDP, ILLG)
BERGER	90	PL B240 237	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
BRESSI	90	NC 103A 731	+Calligarich, Cambiaghi+	(PAVI, ROMA, MILA)
BYRNE	90	PRL 65 289	+Dawber, Spain, Williams+	(SUSS, NBS, SCOT, CBNM)
FREEDMAN	90	CNPP 19 209		(ANL)
GREEN	90	JPG 16 L75	+Thompson	(RAL)
RAMSEY	90	ARNPS 40 1		(HARV)
ROSE	90	PL B234 460	+Zurmuehl, Rullhusen, Ludwig+	(GOET, MPCM, MANZ)
ROSE	90B	NP A514 621	+Zurmuehl, Rullhusen, Ludwig+	(GOET, MPCM)
SMITH	90	PL B234 191	+Crampin+	(SUSS, RAL, HARV, WASH, ILLG, MUNT)
BRESSI	89	ZPHY C43 175	+Calligarich, Cambiaghi+	(INFN, MILA, PAVI, ROMA)
DOVER	89	NIM A284 13	+Gal, Richard	(BNL, HEBR, ISNG)
EROZOLIM...	89	NIM A284 89	Erozolimskii	(PNPI)
KOSSAKOW...	89	NP A503 473	Kossakowski, Grivot+	(LAPP, SAVO, ISNG, ILLG)
MAMPE	89	PRL 63 593	+Ageron, Bates, Pendlebury, Steyerl	(ILLG, RISL, SUSS, URI)
MOHAPATRA	89	NIM A284 1		(UMD)
PAUL	89	ZPHY C45 25	+Anton, Paul, Paul, Mampe	(BONN, WUPP, MPIH, ILLG)
SCHMIEDM...	89	NIM A284 137	Schmiedmayer, Rauch, Riehs	(WIEN)
BAUMANN	88	PR D37 3107	+Gaehler, Kalus, Mampe	(BAYR, MUNI, ILLG)
KOESTER	88	ZPHY A329 229	+Waschkowski, Meier	(MUNI, MUNT)
LAST	88	PRL 60 995	+Arnold, Doehner, Dubbers+	(HEIDP, ILLG, ANL)
SCHMIEDM...	88	PRL 61 1065	Schmiedmayer, Rauch, Riehs	(TUW)
Also	88B	PRL 61 2509 erratum	Schmiedmayer, Rauch, Riehs	(TUW)
SPIVAK	88	JETP 67 1735 Translated from ZETF 94 1.		(KIAE)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
ALTAREV	86	JETPL 44 460 Translated from ZETFP 44 360.	+Borisov, Borovikova, Brandin, Egorov+	(PNPI)
BOPP	86	PRL 56 919	+Dubbers, Hornig, Klemt, Last+	(HEIDP, ANL, ILLG)
Also	88	ZPHY C37 179	Klemt, Bopp, Hornig, Last+	(HEIDP, ANL, ILLG)
CRESTI	86	PL B177 206	+Pasquali, Peruzzo, Pinori, Sartori	(PADO)
Also	88	PL B200 587 erratum	Cresti, Pasquali, Peruzzo, Pinori, Sartori	(PADO)
GREENE	86	PRL 56 819	+Kessler, Deslattes, Boerner	(NBS, ILLG)
KOSVINTSEV	86	JETPL 44 571 Translated from ZETFP 44 444.	+Morozov, Terekhov	(KIAE)
TAKITA	86	PR D34 902	+Arisaka, Kajita, Kifune+	(KEK, TOKY+)
DOVER	85	PR C31 1423	+Gal, Richard	(BNL)
FIDECARO	85	PL 156B 122	+Lanceri+	(CERN, ILLG, PADO, RAL, SUSS)
PARK	85B	NP B252 261	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
JONES	84	PRL 52 720	+Bionta, Blewitt, Bratton+	(IMB Collab.)
PENDLEBURY	84	PL 136B 327	+Smith, Golub, Byrne+	(SUSS, HARV, RAL, ILLG)
CHERRY	83	PRL 50 1354	+Lande, Lee, Steinberg, Cleveland	(PENN, BNL)
DOVER	83	PR D27 1090	+Gal, Richards	(BNL)
KABIR	83	PRL 51 231		(HARV)
MOSTOVOY	83	JETPL 37 196 Translated from ZETFP 37 162.		(KIAE)
ROY	83	PR D28 1770	+Vaidya, Ephraim, Datar, Bhatki+	(TATA)
VAIDYA	83	PR D27 486	+Roy, Ephraim, Datar, Bhattacherjee	(TATA)
GAEHLER	82	PR D25 2887	+Kalus, Mampe	(BAYR, ILLG)
GREENE	82	Metrologia 18 93	+	(YALE, HARV, ILLG, SUSS, ORNL, CENG)
ALTAREV	81	PL 102B 13	+Borisov, Borovikova, Brandin, Egorov+	(PNPI)
BARABANOV	80	JETPL 32 359 Translated from ZETFP 32 384.	+Veretenkin, Gavrin+	(PNPI)
BYRNE	80	PL 92B 274	+Morse, Smith, Shaikh, Green, Greene	(SUSS, RL)
KOSVINTSEV	80	JETPL 31 236 Translated from ZETFP 31 257.	+Kushnir, Morozov, Terekhov	(JINR)
MOHAPATRA	80	PRL 44 1316	+Marshak	(CUNY, VPI)
ALTAREV	79	JETPL 29 730 Translated from ZETFP 29 794.	+Borisov, Brandin, Egorov, Ezhov, Ivanov+	(PNPI)
EROZOLIM...	79	SJNP 30 356 Translated from YAF 30 692.	Erozolimskii, Frank, Mostovoy+	(KIAE)
NORMAN	79	PRL 43 1226	+Seamster	(WASH)
BONDAREN...	78	JETPL 28 303 Translated from ZETFP 28 328.	Bondarenko, Kurguzov, Prokofev+	(KIAE)
Also	82	Smolenice Conf.	Bondarenko	(KIAE)
EROZOLIM...	78	SJNP 28 48 Translated from YAF 28 98.	Erozolimskii, Mostovoy, Fedunin, Frank+	(KIAE)
STRATOWA	78	PR D18 3970	+Dobrozemsky, Weinzierl	(SEIB)
EROZOLIM...	77	JETPL 23 663 Translated from ZETFP 23 720.	Erozolimskii, Frank, Mostovoy+	(KIAE)
STEINBERG	76	PR D13 2469	+Liaud, Vignon, Hughes	(YALE, ISNG)
DOBROZE...	75	PR D11 510	Dobrozemsky, Kerschbaum, Moraw, Paul+	(SEIB)
KROHN	75	PL 55B 175	+Ringo	(ANL)
EROZOLIM...	74	JETPL 20 345 Translated from ZETFP 20 745.	Erozolimskii, Mostovoy, Fedunin, Frank+	
KROPF	74	ZPHY 267 129	+Paul	(LINZ)
Also	70	NP A154 160	Paul	(VIEN)
STEINBERG	74	PRL 33 41	+Liaud, Vignon, Hughes	(YALE, ISNG)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
CHRISTENSEN	72	PR D5 1628	+Nielson, Bahnsen, Brown+	(RISO)
CHRISTENSEN	70	PR C1 1693	+Krohn, Ringo	(ANL)
EROZOLIM...	70C	PL 33B 351	Erozolimskii, Bondarenko, Mostovoy, Obinyakov+	(KIAE)
GRIGOREV	68	SJNP 6 239 Translated from YAF 6 329.	Grigor'ev, Grishin, Vladimirsky, Nikolaevskii+	(ITEP)

NOTE ON N AND Δ RESONANCES

Written December 1997 by R.L. Workman (Virginia Polytechnic Institute and State University).

I. Introduction

The excited states of the nucleon have been studied in a large number of formation and production experiments. The conventional (Breit-Wigner) masses, pole positions, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data. Partial-wave analyses have also been performed on much smaller data sets to get $N\eta$, ΛK, and ΣK branching fractions. Other branching fractions come from isobar-model analyses of $\pi N \rightarrow N\pi\pi$ data. Finally, many $N\gamma$ branching fractions have been determined from photoproduction experiments.

Table 1 lists all the N and Δ entries in the Baryon Listings and gives our evaluation of the status of each, both overall and channel by channel. Only the "established" resonances (overall status 3 or 4 stars) appear in the Baryon Summary Table. We consider a resonance to be established only if it has been seen in at least two independent analyses of elastic scattering and if the relevant partial-wave amplitudes do not behave erratically or have large errors.

Two changes have been made in the Baryon Summary Table: The $\Delta(1900)$ S_{31} state has been downgraded from three stars to two due to its weak signal in speed plots, and thus has been dropped from the Table. More importantly, pole parameters have been added to the Table, as these tend to be less model dependent than parameters found in fits using generalized Breit-Wigner formulas. This point is the subject of the next section.

No new elastic partial-wave analyses have been published since our last *Review*, although some preliminary results were reported at MENU 97 [1], which also contains recent studies of the πN σ term, scattering lengths, and possible isospin-breaking effects.

Several inelastic scattering analyses are now underway [2–5]. Most of them use $\pi N \rightarrow N\eta$ data, together with $\pi N \rightarrow \pi N$ data, in order to obtain improved values of the properties of the $N(1535)$ S_{11}. The Pittsburgh-ANL [2] and Giessen [3] coupled-channel analyses are similar in scope to that of Manley and Saleski [6], but they differ in theoretical approach and in also using electromagnetic channels.

The interested reader will find further discussions in the proceedings of two recent conferences [7,1], and in two older reviews [8,9].

Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****		d	*	**	**	***
$\Delta(1910)$	P_{31}	****	****		e	*	*	*	*
$\Delta(1920)$	P_{33}	***	***		n	*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*		d				
$\Delta(2390)$	F_{37}	*	*		e				
$\Delta(2400)$	G_{39}	**	**		n				
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

References for Section I

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II. Against Breit-Wigner parameters — a pole-emic

Written December 1997 by G. Höhler (University of Karlsruhe).

(1) All theoretical approaches to the resonance phenomenon have in common that the variation of a partial-wave amplitude $T(W)$, where W is the total c.m. energy, is related to a nearly bound state of the projectile-target system (see *e.g.*, Refs. [1–5]). In πN scattering, this state is an excited state of the nucleon (= isobar). The nearly bound state is described in the framework of S-matrix theory by a pole of the S-matrix element at $W_p = M - i\Gamma/2$ in the lower half of the complex W-plane, close to the real axis; M and Γ are called the mass and width of the resonance. The location of the resonance pole is the same for all reactions to which the resonance couples.

In the inelastic region, a resonance is associated with a cluster of poles on different Riemann sheets. If one of these poles is located near the real axis and sufficiently far from branch points, it will be strongly dominant. If one of the final-state particles itself has a strong decay, one also has to consider branch points in the lower half plane that belong to thresholds for two-particle final states (see *e.g.*, Refs. [6,7]).

(2) If the formation of an unstable intermediate particle occurs in a scattering process, one expects *a time-delay between the arrival of the incident wave packet and its departure from the collision region.* Goldberger and Watson [8], starting from earlier work by Wigner, derived for elastic scattering the time-delay Q. Expressed in terms of the amplitude $T(W)$, it is $Q = 2\,Sp(W)$, where $Sp(W) = |dT/dW|$ is the *speed* with which the complex vector T traverses the Argand diagram. If the background can be neglected, a resonance pole leads to a peak of $Sp(W)$ at $W = M$ (see the cited books and Refs. [9–11]).

(3) It is an old tradition that authors of partial-wave analyses determine *conventional resonance parameters* from fits to generalized Breit-Wigner formulas. Each group has its own prescription for the treatment of analyticity, the choice of the background, and other details, so the model-dependence is much larger than in the determination of pole parameters. A serious shortcoming is the poor or missing information on inelastic channels. The conventional parameters are the "mass" m, the "width" $\Gamma(W)$ at $W = m$, and the branching ratios. Following are some problems with these parametrizations.

(a) The conventional $\Delta(1232)$ parameters come from a fit to the P33 partial wave. It is well known from the Chew-Low plot and dispersion relations [12] that this partial wave has a *large background from the nucleon pole term.* The pole position, $1210 - 50\,i$ MeV, belongs to the Δ-resonance, whereas the conventional parameters, $m = 1232$ MeV and $\Gamma(m) = 120$ MeV, belong to the *Δ together with the large background in πN scattering.*

(b) The $N(1535)\ S_{11}$ is *the only 4-star resonance that does not show a signal in the speed plot.* The signal is probably part of the large peak due to the threshold for η production [13]. In this case, poles in other Riemann sheets are expected to give contributions of comparable magnitude. One of these poles produces the threshold cusp [6]. In the 1960's, this problem was treated in many papers (see Ref. 13). In calculations that rely on the conventional mass of 1535 MeV, one cannot see that one has to study a combined resonance plus threshold-cusp phenomenon.

A similar situation of poles in different sheets arises in $\pi\pi$ scattering near the $K\bar{K}$ threshold. See remarks in footnotes to our $f_0(980)$ Listing.

(c) Around 1440 MeV, the VPI group found *two poles in the P_{11} amplitude in different Riemann sheets* [14]. This was interpreted, by other authors, as evidence for the existence of two nearly degenerate P_{11} resonances, in conflict with the constituent quark model. Cutkosky pointed out that the branch point for $\Delta\pi$ decay is located near the poles, so the poles belong to the same resonance. This was confirmed by a new calculation [15], which also led to conventional parameters of $m = 1471$ MeV and $\Gamma(m) = 545$ MeV, which are *much different from the pole parameters,* $1370 - 114\,i$ and $1360 - 120\,i$ MeV. The speed plot confirms that the formation of the unstable particle $N(1440)\ P_{11}$ occurs at a considerably lower energy than expected from the conventional parameters.

Conclusion: *In contrast to the conventional parameters, the pole positions and speed plots have a well-defined relation to S-matrix theory. They also give more information on the resonances and thresholds and can be used for predictions on other reactions that couple to the excited states.*

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III. Electromagnetic interactions

Revised December 1997 by R.L. Crawford (University of Glasgow) and R.L. Workman (Virginia Polytechnic Institute and State University).

Nearly all the entries in the Listings concerning electromagnetic properties of the N and Δ resonances are $N\gamma$ couplings. These couplings, the helicity amplitudes $A_{1/2}$ and $A_{3/2}$, have been obtained in partial-wave analyses of single-pion photoproduction, η photoproduction, and Compton scattering. Most photoproduction analyses take the existence, masses, and widths of the resonances from the $\pi N \to \pi N$ analyses, and only determine the $N\gamma$ couplings. A brief description of the various methods of analysis of photoproduction data may be found in our 1992 edition [1].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [2]. The errors quoted for the couplings in the Listings are calculated in different ways in different analyses and therefore should be used with care. In general, the systematic differences between the analyses caused by using different parameterization schemes are probably more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses, for most resonances, are ARAI 80, CRAWFORD 80, AWAJI 81, FUJII 81, CRAWFORD 83, and ARNDT 96. The $\Delta(1232)$ and $N(1535)$ are special cases, discussed separately below. The errors we give are a combination of the stated statistical errors on the analyses and the systematic differences between them. The analyses are given equal weight, except ARNDT 96 is weighted, rather arbitrarily, by a factor of two because its data set is at least 50% larger than those of the other analyses and contains many new high-quality measurements. Again, the $\Delta(1232)$ and $N(1535)$ are discussed separately below.

The Baryon Summary Table gives $N\gamma$ branching fractions for those resonances whose couplings are considered to be reasonably well established. The $N\gamma$ partial width Γ_γ is given in terms of the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ by

$$\Gamma_\gamma = \frac{k^2}{\pi} \frac{2M_N}{(2J+1)M_R} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right] \quad . \qquad (1)$$

Here M_N and M_R are the nucleon and resonance masses, J is the resonance spin, and k is the photon c.m. decay momentum.

New results for $\Delta(1232) \to p\gamma$: Recent measurements of $\gamma p \to N\pi$ and $\gamma p \to \gamma p$ have fueled a number of new analyses across the first resonance region [3–7]. A central focus has been the E2/M1 ratio, evaluated at the K-matrix and T-matrix poles. The electric quadrupole ($E2$) and magnetic dipole ($M1$) amplitudes are related to our helicity amplitudes by

$$A_{1/2} = -\frac{1}{2}(M1 + 3E2) \quad \text{and} \quad A_{3/2} = -\frac{\sqrt{3}}{2}(M1 - E2) \ . \ (2)$$

Most recent estimates of the E2/M1 ratio, evaluated at the K-matrix pole, are considerably larger (in magnitude) than the average, $-1.5 \pm 0.4\%$, quoted in our 1996 *Review*. This quantity is quite sensitive to the database being fitted. Fits that exclude a few of the older Bonn measurements [8] tend to fall in the range $-2.5 \pm 0.5\%$. (Some analyses of the recent Mainz and BNL measurements suggest a central value closer to -3% [3,7].) The E2/M1 ratio appears to be relatively stable when evaluated at the T-matrix pole [9]. This ratio of pole residues has been added to the Full Listings [10].

Values of $A_{1/2}$ and $A_{3/2}$ from the RPI [3] and VPI [4] analyses are in reasonable agreement. However, the BNL [7] results are quite different, due to their larger cross sections for $\pi^0 p$ photoproduction. Previous estimates of the E2 and M1 amplitudes, at the K- and T-matrix poles, should be considered obsolete. Pole parameters given for the $\Delta^+(1232)$ in our 1996 *Review* are also obsolete (see Ref. [11]).

New results for $N(1535) \to p\gamma$: Properties of the $N(1535)$ are difficult to extract from $\pi N \to \pi N$ and $\gamma N \to \pi N$ due to the nearby ηN threshold (see Sec. III). As a result, a number of recent analyses have been based on data from $\pi^- p \to \eta n$ and $\gamma p \to \eta p$. These studies, and those based on coupled-channel analyses including pion photoproduction data, generally find results [12–15] for $A_{1/2}$ that are significantly different from those based on pion photoproduction alone. In particular, $A_{1/2}$ is sensitive to the $N(1535)$ mass and width, and to its interference with the $N(1650)$ [15].

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IV. Outlook

Revised November 1997 by D.M. Manley (Kent State University).

In May 1997, a new program in baryon spectroscopy was initiated at the Brookhaven National Laboratory AGS with the Crystal Ball Spectrometer [1]. AGS Expt. E913 measures over most of a 4π solid angle the reactions $\pi^- p \to \gamma n$, $\pi^0 n$, ηn, and $\pi^0\pi^0 n$ at 12 momenta between 285 and 750 MeV/c. These measurements will be completed in 1998, and then AGS Expt. E914 will begin a study of hyperon resonances using the reactions $K^- p \to$ neutrals.

Most of the new generation of experiments to study baryon spectroscopy will use electromagnetic probes. Commissioning experiments were carried out for the CEBAF Large Acceptance Spectrometer, CLAS, during mid 1997, using electron beams with energies of 1.6, 2.4, and 4.0 GeV. The first physics run began in December 1997. Initial measurements of $ep \to eX$ will be performed with 1.6- and 2.4-GeV electrons. Measurements with 4.0-GeV electrons are scheduled for early 1998. Runs with tagged photons are scheduled for early Spring and Summer, 1998. A number of experiments at CEBAF to study baryon resonances have already been completed, including studies of the $(e, e'K^+)$ reactions on hydrogen and deuterium targets [2], and studies of the $e^- p \to e^- p\eta$ reaction [3]. The $E2/M1$ ratio is being investigated using new measurements of the $p\,(e, e'p)\pi^0$ reaction near the $\Delta(1232)$ resonance, and new measurements of $p(e, e'\vec{p})\pi^0$ at the MIT-Bates Lab [4].

Much work is also underway in European facilities. For example, in 1996, studies of η and K photoproduction commenced at GRAAL in Grenoble [5]. This lab currently provides photon beams with energies up to 1.5 GeV, and may later upgrade to 1.8 GeV. Several reactions are under study there, including $\gamma p \to \gamma p$, ηp, $\pi^0 p$, $\pi^+ n$, and $\pi^0\pi^0 p$. New meson photoproduction data are also being produced from experiments using the 855-MeV CW electron accelerator MAMI at Mainz, which produces photon beams with energies up to 800 MeV [6]. For example, new experiments of pion photoproduction with linearly polarized photons having energies up to 500 MeV are providing data on the $E2/M1$ ratio for the $\Delta(1232)$ resonance.

Space does not permit a full discussion of the large amount of experimental work now underway at the labs already mentioned, or at other labs such as Bonn. The new experiments have also inspired many new theoretical and phenomenological efforts to understand this particular aspect of nonperturbative QCD. These efforts include techniques such as lattice gauge theory, phenomenological Lagrangians, constituent quark-model calculations, and various unitary multichannel approaches.

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V. Non-qqq baryon candidates

The standard quark-model assignments for baryons are outlined in Sec. 13.3, "Baryons: qqq states." Just as with mesons (see the "Note on Non-$q\bar{q}$ mesons"), there have been suggestions that non-qqq baryons might exist, such as hybrid ($qqqg$) baryons and unstable meson-nucleon bound states [1] (see the "Note on the $\Lambda(1405)$").

If non-qqq states exist, they will be more difficult to identify than hybrid mesons: They will not have the clean signature of exotic quantum numbers, and they should also mix with ordinary qqq states. Their identification will depend upon (a) characteristics of their formation and decay, and (b) an over-population of expected qqq states.

Most investigations have focused on the properties of the lightest predicted hybrids. If the first hybrid state lies below 2 GeV, as is suggested by bag-model calculations [2,3,4], it may already exist in our Listings. (However, some estimates put the lightest state well above 2 GeV [5].) At present, there are actually not enough known resonances to fill the known multiplets. If an existing resonance is identified as a hybrid, yet another ordinary qqq state must be found.

The Roper resonance, the $N(1440)\,P_{11}$, has been a hybrid candidate based upon its quantum numbers [2] and difficulties with its mass and electromagnetic couplings. If it were a hybrid, our interpretation of the low-lying P_{11}, P_{13}, P_{31}, and P_{33} resonances would change [2,6]. In Ref. 6, both the $N(1440)\,P_{11}$ and $\Delta(1600)\,P_{33}$ are hybrid candidates, and $N(1540)\,P_{13}$ and $\Delta(1550)\,P_{31}$ states are predicted. One-star P_{13} and P_{31} states were listed in our 1990 Review [7] but were then removed.

Both photoproduction [6,8,9] and electroproduction [9,10] have been considered in the search for a unique hybrid signature. In Ref. 11, QCD counting rules were used to reveal a characteristic of hybrid electroproduction at high Q^2. If the $N(1440)$ is a hybrid, its transverse form factor is expected to fall asymptotically $O(1/Q^2)$ faster than for a pure qqq state. However, mixing between qqq and $qqqg$ states will make this identification difficult.

A number of recent experiments have searched for pentaquark ($qqqq\bar{q}$) resonances and H dibaryons ($uuddss$ states). Narrow structures found in proton-nucleus scattering [12] have been attributed to $qqqs\bar{s}$ states, but these need confirmation. The H-dibaryon experiments, while finding possible candidates [13], have generally quoted upper limits [14] for exotic resonance production. Searches for narrow dibaryons in the nucleon-nucleon interaction are also continuing [15].

Finally, there has been a report [16] of resonances lying below the $\Delta(1232)$. A very weak signal was found using the reaction $pp \rightarrow \pi^+ p X^0$. An earlier search [17] for isospin-3/2 states, using $pp \rightarrow n X^{++}$, found a null result in the mass range between M_N and $M_N + M_\pi$. At present, there appears to be no evidence for such low-mass states from other reactions.

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$N(1440)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1440)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1430 to 1470 (≈ 1440) OUR ESTIMATE				
1462±10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1440±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1410±12	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1463± 7	ARNDT	96	IPWA	$\gamma N \to \pi N$
1467	ARNDT	95	DPWA	$\pi N \to N\pi$
1421±18	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1465	LI	93	IPWA	$\gamma N \to \pi N$
1471	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1411	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1472	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
1417	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1460	BERENDS	77	IPWA	$\gamma N \to \pi N$
1380	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1390	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1440)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
250 to 450 (≈ 350) OUR ESTIMATE				
391± 34	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
545±170	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
340± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
135± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
360± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
440	ARNDT	95	DPWA	$\pi N \to N\pi$
250± 63	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
315	LI	93	IPWA	$\gamma N \to \pi N$
334	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
113	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
331	BARBOUR	78	DPWA	$\gamma N \to \pi N$
279	BERENDS	77	IPWA	$\gamma N \to \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
200	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1440)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1345 to 1385 (≈ 1365) OUR ESTIMATE				
1346	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
1385	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
1370	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1375±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1360	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1381 or 1379	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1360 or 1333	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
160 to 260 (≈ 210) OUR ESTIMATE				
176	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
164	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
228	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
180±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
252	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
209 or 210	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
167 or 234	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1440)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
42	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
40	HOEHLER	93	SPED	$\pi N \to \pi N$
74	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
52±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
109	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−101	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
− 84	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
−100±35	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 93	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1440)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	30–40 %
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	<8 %
Γ_7	$N\rho$, $S=1/2$, P-wave	
Γ_8	$N\rho$, $S=3/2$, P-wave	
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–10 %
Γ_{10}	$p\gamma$	0.035–0.048 %
Γ_{11}	$p\gamma$, helicity=1/2	0.035–0.048 %
Γ_{12}	$n\gamma$	0.009–0.032 %
Γ_{13}	$n\gamma$, helicity=1/2	0.009–0.032 %

$N(1440)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.6 to 0.7 OUR ESTIMATE				
0.69±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.68±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.51±0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.68	ARNDT	95	DPWA	$\pi N \to N\pi$
0.56±0.08	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1440) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.328	[8] FELTESSE	75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1440) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.37 to +0.41 OUR ESTIMATE				
+0.39±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.41	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.37	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1440) \to N\rho$, $S=1/2$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
±0.07 to ±0.25 OUR ESTIMATE				
−0.11	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1440) \to N\rho$, $S=3/2$, P-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.18	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1440) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
±0.17 to ±0.25 OUR ESTIMATE				
+0.24±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.18	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1440)$ PHOTON DECAY AMPLITUDES

$N(1440) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.065 ±0.004 OUR ESTIMATE				
−0.063 ±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.069 ±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.063 ±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.069 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.066 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.079 ±0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
−0.068 ±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.0584±0.0148	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.085 ±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.129	[10] WADA	84	DPWA	Compton scattering
−0.075 ±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.125	[11] NOELLE	78		$\gamma N \to \pi N$
−0.076	BERENDS	77	IPWA	$\gamma N \to \pi N$
−0.087 ±0.006	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1440) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.040±0.010 OUR ESTIMATE				
0.045±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.037±0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.030±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.023±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.019±0.012	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.056±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.029±0.035	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.085±0.006	LI	93	IPWA	$\gamma N \to \pi N$
+0.059±0.016	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.062	[11] NOELLE	78		$\gamma N \to \pi N$

$N(1440)$ FOOTNOTES

[1] BAKER 79 finds a coupling of the $N(1440)$ to the $N\eta$ channel near (but slightly below) threshold.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] ARNDT 95 also finds a second-sheet pole with real part = 1383 MeV, −2×imaginary part = 210 MeV, and residue with modulus 92 MeV and phase = -54°.

[5] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[6] ARNDT 91 (Soln SM90) also finds a second-sheet pole with real part = 1413 MeV, −2 × imaginary part = 256 MeV, and residue = $(78-153i)$ MeV.

[7] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[8] An alternative which cannot be distinguished from this is to have a P_{13} resonance with M = 1530 MeV, Γ = 79 MeV, and elasticity = +0.271.

[9] LONGACRE 77 considers this coupling to be well determined.

[10] WADA 84 is inconsistent with other analyses; see the Note on N and Δ Resonances.

[11] Converted to our conventions using M = 1486 MeV, Γ = 613 MeV from NOELLE 78.

$N(1440)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	90	PR D42 235	+Wang	(CMU)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1520)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1520)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1515 to 1530 (≈ 1520) OUR ESTIMATE				
1524± 4	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1525±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1519± 4	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1516±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1515	ARNDT	95	DPWA	$\pi N \to N\pi$
1526±18	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1510	LI	93	IPWA	$\gamma N \to \pi N$
1504	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1503	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1510	BERENDS	77	IPWA	$\gamma N \to \pi N$
1510	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1520	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 to 135 (≈ 120) OUR ESTIMATE				
124± 8	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
120±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
114± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
106± 4	ARNDT	96	IPWA	$\gamma N \to \pi N$
106	ARNDT	95	DPWA	$\pi N \to N\pi$
143±32	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
120	LI	93	IPWA	$\gamma N \to \pi N$
124	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
183	BAKER	79	DPWA	$\pi^- p \to n\eta$
135	BARBOUR	78	DPWA	$\gamma N \to \pi N$
105	BERENDS	77	IPWA	$\gamma N \to \pi N$
110	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1505 to 1515 (≈ 1510) OUR ESTIMATE				
1515	ARNDT	95	DPWA	$\pi N \to N\pi$
1510	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
1510±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1511	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1514 or 1511	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1508 or 1505	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 to 120 (≈ 115) OUR ESTIMATE				
110	ARNDT	95	DPWA	$\pi N \to N\pi$
120	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
114±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
108	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
146 or 137	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
109 or 107	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1520) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
34	ARNDT	95	DPWA	$\pi N \to N\pi$
32	HOEHLER	93	ARGD	$\pi N \to \pi N$
35 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
33	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
7	ARNDT	95	DPWA	$\pi N \to N\pi$
-8	HOEHLER	93	ARGD	$\pi N \to \pi N$
-12 ± 5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-10	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1520) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	50–60 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	40–50 %
Γ_4	$\Delta\pi$	15–25 %
Γ_5	$\Delta(1232)\pi$, *S*-wave	5–12 %
Γ_6	$\Delta(1232)\pi$, *D*-wave	10–14 %
Γ_7	$N\rho$	15–25 %
Γ_8	$N\rho$, S=1/2, *D*-wave	
Γ_9	$N\rho$, S=3/2, *S*-wave	
Γ_{10}	$N\rho$, S=3/2, *D*-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %
Γ_{12}	$p\gamma$	0.46–0.56 %
Γ_{13}	$p\gamma$, helicity=1/2	0.001–0.034 %
Γ_{14}	$p\gamma$, helicity=3/2	0.44–0.53 %
Γ_{15}	$n\gamma$	0.30–0.53 %
Γ_{16}	$n\gamma$, helicity=1/2	0.04–0.10 %
Γ_{17}	$n\gamma$, helicity=3/2	0.25–0.45 %

N(1520) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.5 to 0.6 OUR ESTIMATE				
0.59 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.58 ± 0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.54 ± 0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.61	ARNDT	95	DPWA	$\pi N \to N\pi$
0.46 ± 0.06	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001 ± 0.002	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.02	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.011	FELTESSE	75	DPWA	Soln A; see BAKER 79

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, *S*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26 to −0.20 OUR ESTIMATE				
-0.18 ± 0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
-0.26	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.24	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, *D*-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.28 to −0.24 OUR ESTIMATE				
-0.29 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
-0.21	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to N\rho$, S=3/2, *S*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.35 to −0.31 OUR ESTIMATE				
-0.35 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
-0.35	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.24	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.22 to −0.06 OUR ESTIMATE				
-0.13	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.17	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1520) PHOTON DECAY AMPLITUDES

$N(1520) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.024 ± 0.009 OUR ESTIMATE				
-0.020 ± 0.007	ARNDT	96	IPWA	$\gamma N \to \pi N$
-0.028 ± 0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.007 ± 0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.032 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.032 ± 0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.031 ± 0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
-0.019 ± 0.007	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.0430 ± 0.0063	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.020 ± 0.002	LI	93	IPWA	$\gamma N \to \pi N$
-0.012	WADA	84	DPWA	Compton scattering
-0.016 ± 0.008	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.008	[6] NOELLE	78		$\gamma N \to \pi N$
-0.021	BERENDS	77	IPWA	$\gamma N \to \pi N$
-0.005 ± 0.005	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1520) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
$+0.166 \pm0.005$ OUR ESTIMATE				
0.167 ± 0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.156 ± 0.022	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.168 ± 0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.178 ± 0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.162 ± 0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.166 ± 0.005	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
0.167 ± 0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.1695 ± 0.0014	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.167 ± 0.002	LI	93	IPWA	$\gamma N \to \pi N$
0.168	WADA	84	DPWA	Compton scattering
$+0.157\pm0.007$	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.206	[6] NOELLE	78		$\gamma N \to \pi N$
+0.075	BERENDS	77	IPWA	$\gamma N \to \pi N$
$+0.164\pm0.008$	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1520) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.059 ± 0.009 OUR ESTIMATE				
-0.048 ± 0.008	ARNDT	96	IPWA	$\gamma N \to \pi N$
-0.066 ± 0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.067 ± 0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
-0.076 ± 0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.071 ± 0.011	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.056 ± 0.011	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.050 ± 0.014	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.058 ± 0.003	LI	93	IPWA	$\gamma N \to \pi N$
-0.055 ± 0.014	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.060	[6] NOELLE	78		$\gamma N \to \pi N$

$N(1520) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.139 ± 0.011 OUR ESTIMATE				
-0.140 ± 0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
-0.124 ± 0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.158 ± 0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
-0.147 ± 0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.148 ± 0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.144 ± 0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.118 ± 0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.131 ± 0.003	LI	93	IPWA	$\gamma N \to \pi N$
-0.141 ± 0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.127	[6] NOELLE	78		$\gamma N \to \pi N$

$N(1520)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] LONGACRE 77 considers this coupling to be well determined.

[6] Converted to our conventions using $M = 1528$ MeV, $\Gamma = 187$ MeV from NOELLE 78.

$N(1520)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)	
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)	
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)	
HOEHLER	93	πN Newsletter 9 1		(KARL)	
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)	
MANLEY	92	PR D45 4002	+Saleski	(KENT)	IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)	
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE)	IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)	
CRAWFORD	83	NP B211 1	+Morton	(GLAS)	
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)	
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)	
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)	
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)	
ARAI	80	Toronto Conf. 93		(INUS)	
Also	82	NP B194 251	Arai, Fujii	(INUS)	
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)	
CRAWFORD	80	Toronto Conf. 107		(GLAS)	
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)	IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)	IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)	
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)	
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL)	IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT)	IJP
Also	80	Toronto Conf. 3	Koch	(KARLT)	IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)	
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)	
NOELLE	78	PTP 60 778		(NAGO)	
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS)	IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL)	IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL)	IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK)	IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL)	IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC)	IJP

$N(1535)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1535)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1520 to 1555 (≈ 1535) OUR ESTIMATE				
1534± 7	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1550±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1526± 7	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1549± 2	ABAEV	96	DPWA	$\pi^- p \rightarrow \eta n$
1525±10	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
1535	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1542± 6	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
1537	BATINIC	95B	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
1544±13	KRUSCHE	95	DPWA	$\gamma p \rightarrow p\eta$
1518	LI	93	IPWA	$\gamma N \rightarrow \pi N$
1513	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1511	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1500	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$
1547± 6	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1520	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1510	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 150) OUR ESTIMATE				
148.2± 8.1	GREEN	97	DPWA	$\pi N \rightarrow \pi N$, ηN
151 ±27	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
240 ±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
120 ±20	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
212 ±20	[3] KRUSCHE	97	DPWA	$\gamma N \rightarrow \eta N$
169 ±12	ABAEV	96	DPWA	$\pi^- p \rightarrow \eta n$
103 ± 5	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
66	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
150 ±15	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
145	BATINIC	95B	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
200 ±40	KRUSCHE	95	DPWA	$\gamma p \rightarrow p\eta$
84	LI	93	IPWA	$\gamma N \rightarrow \pi N$
136	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
180	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
132	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
57	BERENDS	77	IPWA	$\gamma N \rightarrow \pi N$
139 ±33	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
100	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1495 to 1515 (≈ 1505) OUR ESTIMATE				
1501	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1487	[4] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
1510±50	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1499	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1496 or 1499	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1519± 4	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1525 or 1527	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
90 to 250 (≈ 170) OUR ESTIMATE				
124	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
260±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
110	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
103 or 105	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
140±32	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135 or 123	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1535)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
31	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
120±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
23	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−12	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
+15±45	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−13	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

$N(1535)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–55 %
Γ_2	$N\eta$	30–55 %
Γ_3	$N\pi\pi$	1–10 %
Γ_4	$\Delta\pi$	<1 %
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	<4 %
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<3 %
Γ_{10}	$N(1440)\pi$	<7 %
Γ_{11}	$p\gamma$	0.15–0.35 %
Γ_{12}	$p\gamma$, helicity=1/2	0.15–0.35 %
Γ_{13}	$n\gamma$	0.004–0.29 %
Γ_{14}	$n\gamma$, helicity=1/2	0.004–0.29 %

$N(1535)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.35 to 0.55 OUR ESTIMATE			
0.394±0.009	GREEN 97	DPWA	$\pi N \rightarrow \pi N, \eta N$
0.51 ±0.05	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.50 ±0.10	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
0.38 ±0.04	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.31	ARNDT 95	DPWA	$\pi N \rightarrow N\pi$
0.34 ±0.09	BATINIC 95	DPWA	$\pi N \rightarrow N\pi, N\eta$
0.297±0.026	BHANDARI 77	DPWA	Uses $N\eta$ cusp

$\Gamma(N\eta)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
+0.30 to 0.55 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.568±0.011	GREEN 97	DPWA	$\pi N \rightarrow \pi N, \eta N$
0.59 ±0.02	ABAEV 96	DPWA	$\pi^- p \rightarrow \eta n$
0.63 ±0.07	BATINIC 95	DPWA	$\pi N \rightarrow N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1535) \rightarrow N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.44 to +0.50 OUR ESTIMATE			
+0.47±0.02	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.33	BAKER 79	DPWA	$\pi^- p \rightarrow n\eta$
+0.48	FELTESSE 75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1535) \rightarrow \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.04 to +0.06 OUR ESTIMATE			
+0.00±0.04	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.00	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.06	[2] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1535) \rightarrow N\rho$, $S=1/2$, S-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.14 to −0.06 OUR ESTIMATE			
−0.10±0.03	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
−0.10	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.09	[2] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1535) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.03 to +0.13 OUR ESTIMATE			
+0.07±0.04	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
+0.08	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.09	[2] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1535) \rightarrow N(1440)\pi$ — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.10±0.05	MANLEY 92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$N(1535)$ PHOTON DECAY AMPLITUDES

$N(1535) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.090 ±0.030 OUR ESTIMATE			
0.120 ±0.011 ±0.015	[3] KRUSCHE 97	DPWA	$\gamma N \rightarrow \eta N$
0.060 ±0.015	ARNDT 96	IPWA	$\gamma N \rightarrow \pi N$
0.097 ±0.006	BENMERROU..95	DPWA	$\gamma N \rightarrow N\eta$
0.095 ±0.011	[6] BENMERROU..91		$\gamma p \rightarrow p\eta$
0.053 ±0.015	CRAWFORD 83	IPWA	$\gamma N \rightarrow \pi N$
0.077 ±0.021	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
0.083 ±0.007	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.080 ±0.007	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.029 ±0.007	BRATASHEV... 80	DPWA	$\gamma N \rightarrow \pi N$
0.065 ±0.016	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
0.0704±0.0091	ISHII 80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.110 to 0.140	KRUSCHE 95	DPWA	$\gamma p \rightarrow p\eta$
0.125 ±0.025	KRUSCHE 95C	IPWA	$\gamma d \rightarrow \eta N(N)$
0.061 ±0.003	LI 93	IPWA	$\gamma N \rightarrow \pi N$
0.055	WADA 84	DPWA	Compton scattering
+0.082 ±0.019	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$
0.046	[7] NOELLE 78		$\gamma N \rightarrow \pi N$
+0.034	BERENDS 77	IPWA	$\gamma N \rightarrow \pi N$
+0.070 ±0.004	FELLER 76	DPWA	$\gamma N \rightarrow \pi N$

$N(1535) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.046±0.027 OUR ESTIMATE			
−0.020±0.035	ARNDT 96	IPWA	$\gamma N \rightarrow \pi N$
0.035±0.014	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
−0.062±0.003	FUJII 81	DPWA	$\gamma N \rightarrow \pi N$
−0.075±0.019	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.075±0.018	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.098±0.026	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
−0.011±0.017	TAKEDA 80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.100±0.030	KRUSCHE 95C	IPWA	$\gamma d \rightarrow \eta N(N)$
−0.046±0.005	LI 93	IPWA	$\gamma N \rightarrow \pi N$
−0.112±0.034	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$
−0.048	[7] NOELLE 78		$\gamma N \rightarrow \pi N$

$N(1535) \rightarrow N\gamma$, ratio $A^n_{1/2}/A^p_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
−0.84±0.15	MUKHOPAD... 95B	IPWA

$N(1535)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] KRUSCHE 97 fits with the mass fixed at 1544 MeV.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] BENMERROUCHE 91 uses an effective Lagrangian approach to analyze η photoproduction data.

[7] Converted to our conventions using M = 1548 MeV, Γ = 73 MeV from NOELLE 78.

$N(1535)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

GREEN	97	PR C55 R2167	+Wycech	(HELS, WINR)
KRUSCHE	97	PL B397 171	+Mukhopadhyay, Zhang+	(GIES, RPI, SASK)
ABAEV	96	PR C53 385	+Nefkens	(UCLA)
ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
BATINIC	95B	PR C52 2188	+Slaus, Svarc	(BOSK)
BENMERROU...	95	PR D51 3237	Benmerrouche, Mukhopadhyay, Zhang	(RPI, SASK)
KRUSCHE	95	PRL 74 3736	+Ahrens, Anton+	(GIES, MANZ, GLAS, BONN, DARM)
KRUSCHE	95C	PL B358 40	+Ahrens+	(GIES, MANZ, GLAS, BONN, DARM)
MUKHOPAD...	95B	PL B364 1	Mukhopadhyay, Zhang, Benmerrouche	(RPI, SASK)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BENMERROU...	91	PRL 67 1070	Benmerrouche, Mukhopadhyay	(RPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
BHANDARI	77	PR D15 192	+Chao	(CMU) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

N(1650) S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1650) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1640 to 1680 (≈ 1650) OUR ESTIMATE				
1659± 9	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1650±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1670± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1677± 8	ARNDT	96	IPWA	$\gamma N \to \pi N$
1667	ARNDT	95	DPWA	$\pi N \to N\pi$
1712	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
1669±17	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1713±27	[2] BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1674	LI	93	IPWA	$\gamma N \to \pi N$
1688	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1672	MUSETTE	80	IPWA	$\pi^- p \to \Lambda K^0$
1680	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1694	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1700± 5	[3] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1680	[3] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1700	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1675	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1660	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1650) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
145 to 190 (≈ 150) OUR ESTIMATE				
167.9± 9.4	GREEN	97	DPWA	$\pi N \to \pi N, \eta N$
173 ±12	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
150 ±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
180 ±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
160 ±12	ARNDT	96	IPWA	$\gamma N \to \pi N$
90	ARNDT	95	DPWA	$\pi N \to N\pi$
184	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
215 ±32	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
279 ±54	[2] BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
225	LI	93	IPWA	$\gamma N \to \pi N$
183	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
179	MUSETTE	80	IPWA	$\pi^- p \to \Lambda K^0$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
90	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
193	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130 ±10	[3] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
90	[3] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
170	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
170	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
130	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1650) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1640 to 1680 (≈ 1660) OUR ESTIMATE				
1673	ARNDT	95	DPWA	$\pi N \to N\pi$
1689	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
1670	[6] HOEHLER	93	ARGD	$\pi N \to \pi N$
1640±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1657	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1648 or 1651	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1699 or 1698	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 170 (≈ 160) OUR ESTIMATE				
82	ARNDT	95	DPWA	$\pi N \to N\pi$
192	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
163	[6] HOEHLER	93	ARGD	$\pi N \to \pi N$
150±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
160	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
117 or 119	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
174 or 173	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1650) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
22	ARNDT	95	DPWA	$\pi N \to N\pi$
72	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
39	HOEHLER	93	ARGD	$\pi N \to \pi N$
60±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
54	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
29	ARNDT	95	DPWA	$\pi N \to N\pi$
−85	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
−37	HOEHLER	93	ARGD	$\pi N \to \pi N$
−75±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−38	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1650) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–90 %
Γ_2	$N\eta$	3–10 %
Γ_3	ΛK	3–11 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	10–20 %
Γ_6	$\Delta\pi$	1–7 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$N\rho$	4–12 %
Γ_9	$N\rho$, $S=1/2$, S-wave	
Γ_{10}	$N\rho$, $S=3/2$, D-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<4 %
Γ_{12}	$N(1440)\pi$	<5 %
Γ_{13}	$p\gamma$	0.04–0.18 %
Γ_{14}	$p\gamma$, helicity=1/2	0.04–0.18 %
Γ_{15}	$n\gamma$	0.003–0.17 %
Γ_{16}	$n\gamma$, helicity=1/2	0.003–0.17 %

N(1650) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.55 to 0.90 OUR ESTIMATE				
0.735±0.011	GREEN	97	DPWA	$\pi N \to \pi N, \eta N$
0.89 ±0.07	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.65 ±0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.61 ±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.99	ARNDT	95	DPWA	$\pi N \to N\pi$
0.27	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
0.94 ±0.07	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
0.49 ±0.21	[2] BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.06±0.05	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
0.02±0.03	[2] BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.09	[8] BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.27 to −0.17 OUR ESTIMATE				
−0.22	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.22	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.25	[9] BAKER	78	DPWA	See SAXON 80
−0.23±0.01	[3] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.25	[3] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.12	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.254	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.066 to 0.137	[10] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.20	KNASEL	75	DPWA	

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to \Delta(1232)\pi$, *D*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15 to 0.23 OUR ESTIMATE				
+0.12±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.29	[4,11] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.15	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to N\rho$, S=1/2, *S*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.03 to ±0.19 OUR ESTIMATE				
−0.01±0.09	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.17	[4,11] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.16	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to N\rho$, S=3/2, *D*-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.17 to +0.29 OUR ESTIMATE				
+0.16±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.29	[4,11] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04 to +0.18 OUR ESTIMATE				
+0.12±0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.00	[4,11] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.25	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1650) \to N(1440)\pi$ $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$N(1650)$ PHOTON DECAY AMPLITUDES

$N(1650) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.053±0.016 OUR ESTIMATE				
0.069±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.033±0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.050±0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.065±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.061±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.031±0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.068±0.003	LI	93	IPWA	$\gamma N \to \pi N$
0.091	WADA	84	DPWA	Compton scattering
+0.048±0.017	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.068±0.009	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1650) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.015±0.021 OUR ESTIMATE				
−0.015±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.008±0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
0.010±0.020	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.008±0.019	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.068±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.011±0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.002±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.045±0.024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1650)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $p\gamma \to N(1650) \to \Lambda K^+$ (E_{0+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
7.8 ±0.3	WORKMAN	90	DPWA
8.13	TANABE	89	DPWA

$p\gamma \to N(1650) \to \Lambda K^+$ phase angle θ (E_{0+} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−107 ±3	WORKMAN	90	DPWA
−107.8	TANABE	89	DPWA

$N(1650)$ FOOTNOTES

[1] ARNDT 95 finds two distinct states.

[2] BATINIC 95 finds two distinct states. This second resonance was associated with the $N(2090)$ S_{11}.

[3] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[4] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[5] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[6] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[7] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[8] BAKER 79 fixed this coupling during fitting, but the negative sign relative to the $N(1535)$ is well determined.

[9] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions. Superseded by SAXON 80.

[10] The range given for DEANS 75 is from the four best solutions.

[11] LONGACRE 77 considers this coupling to be well determined.

$N(1650)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

GREEN	97	PR C55 R2167	+Wycech	(HELS, WINR)	
ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)	
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)	
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)	
HOEHLER	93	πN Newsletter 9 1		(KARL)	
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)	
MANLEY	92	PR D45 4002	+Saleski	(KENT)	IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)	
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE)	IJP
WORKMAN	90	PR C42 781		(VPI)	
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)	
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)	
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)	
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL)	IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)	
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)	
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)	
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)	
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)	
ARAI	80	Toronto Conf. 93		(INUS)	
Also	82	NP B194 251	Arai, Fujii	(INUS)	
CRAWFORD	80	Toronto Conf. 107		(GLAS)	
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)	IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)	IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL)	IJP
MUSETTE	80	NC 57A 37		(BRUX)	IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS)	IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)	
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL)	IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT)	IJP
Also	80	Toronto Conf. 3	Koch	(KARLT)	IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE)	IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)	
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)	
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL)	IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL)	IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL)	IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK)	IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH)	IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL)	IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC)	IJP

N(1675) D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1675) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1670 to 1685 (≈ 1675) OUR ESTIMATE				
1676± 2	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1675±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1679± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1673± 5	ARNDT	96	IPWA	$\gamma N \to \pi N$
1673	ARNDT	95	DPWA	$\pi N \to N\pi$
1683±19	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1666	LI	93	IPWA	$\gamma N \to \pi N$
1685	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1670	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1660	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1675) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
140 to 180 (≈ 150) OUR ESTIMATE				
159± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
160±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
154± 7	ARNDT	96	IPWA	$\gamma N \to \pi N$
154	ARNDT	95	DPWA	$\pi N \to N\pi$
142±23	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
136	LI	93	IPWA	$\gamma N \to \pi N$
191	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
40	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
88	BAKER	79	DPWA	$\pi^- p \to n\eta$
192	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1675) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1655 to 1665 (≈ 1660) OUR ESTIMATE				
1663	ARNDT	95	DPWA	$\pi N \to N\pi$
1656	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
1660±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1655	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1663 or 1668	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1649 or 1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125 to 155 (≈ 140) OUR ESTIMATE				
152	ARNDT	95	DPWA	$\pi N \to N\pi$
126	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
140±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
124	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
146 or 171	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
127 or 127	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1675) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
29	ARNDT	95	DPWA	$\pi N \to N\pi$
23	HOEHLER	93	ARGD	$\pi N \to \pi N$
31±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
28	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
− 6	ARNDT	95	DPWA	$\pi N \to N\pi$
−22	HOEHLER	93	ARGD	$\pi N \to \pi N$
−30±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−17	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1675) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	40–50 %
Γ_2	$N\eta$	
Γ_3	ΛK	<1 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	50–60 %
Γ_6	$\Delta\pi$	50–60 %
Γ_7	$\Delta(1232)\pi$, *D*-wave	
Γ_8	$\Delta(1232)\pi$, *G*-wave	
Γ_9	$N\rho$	< 1–3 %
Γ_{10}	$N\rho$, S=1/2, *D*-wave	
Γ_{11}	$N\rho$, S=3/2, *D*-wave	
Γ_{12}	$N\rho$, S=3/2, *G*-wave	
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{14}	$p\gamma$	0.004–0.023 %
Γ_{15}	$p\gamma$, helicity=1/2	0.0–0.015 %
Γ_{16}	$p\gamma$, helicity=3/2	0.0–0.011 %
Γ_{17}	$n\gamma$	0.02–0.12 %
Γ_{18}	$n\gamma$, helicity=1/2	0.006–0.046 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.08 %

N(1675) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.4 to 0.5 OUR ESTIMATE				
0.47±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.38±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.38	ARNDT	95	DPWA	$\pi N \to N\pi$
0.31±0.06	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.001	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\eta$ — $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.07	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.009	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
±0.04 to ±0.08 OUR ESTIMATE				
−0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.036	[5] SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034±0.006	DEVENISH	74B		Fixed-*t* dispersion rel.

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Delta(1232)\pi$, *D*-wave — $(\Gamma_1\Gamma_7)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.46 to +0.50 OUR ESTIMATE				
+0.496±0.003	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.46	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.50	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.5	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\rho$, S=1/2, *D*-wave — $(\Gamma_1\Gamma_{10})^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.04±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\rho$, $S{=}3/2$, D-wave $\qquad (\Gamma_1\Gamma_{11})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.12 to −0.06 OUR ESTIMATE				
−0.03±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.15	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $\qquad (\Gamma_1\Gamma_{13})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ PHOTON DECAY AMPLITUDES

$N(1675) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.019±0.008 OUR ESTIMATE				
0.015±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.021±0.011	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.034±0.005	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.006±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.006±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.023±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.022±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.034±0.004	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1675) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.015±0.009 OUR ESTIMATE				
0.010±0.007	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.015±0.009	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.024±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.030±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.029±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.003±0.012	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.021±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.015±0.006	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.019±0.009	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1675) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.043±0.012 OUR ESTIMATE				
−0.049±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.057±0.024	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.033±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.039±0.017	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.025±0.027	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.059±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.021±0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.060±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.066±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1675) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.058±0.013 OUR ESTIMATE				
−0.051±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.077±0.018	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.069±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.066±0.026	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.071±0.022	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.059±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.030±0.012	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.074±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.073±0.014	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1675)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] SAXON 80 finds the coupling phase is near 90°.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1675)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1680)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1680)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1675 to 1690 (≈ 1680) OUR ESTIMATE				
1684± 4	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1680±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1684± 3	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1679± 5	ARNDT	96	IPWA	$\gamma N \to \pi N$
1678	ARNDT	95	DPWA	$\pi N \to N\pi$
1674±12	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1682	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1660	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1685	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1670	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120 to 140 (≈ 130) OUR ESTIMATE				
139± 8	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
120±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
128± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
124± 4	ARNDT	96	IPWA	$\gamma N \to \pi N$
126	ARNDT	95	DPWA	$\pi N \to N\pi$
126±20	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
121	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
119	BARBOUR	78	DPWA	$\gamma N \to \pi N$
150	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
155	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1665 to 1675 (≈ 1670) OUR ESTIMATE				
1670	ARNDT	95	DPWA	$\pi N \to N\pi$
1673	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
1667±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1670	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1668 or 1674	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1656 or 1653	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
105 to 135 (≈ 120) OUR ESTIMATE				
120	ARNDT	95	DPWA	$\pi N \to N\pi$
135	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
110 ± 10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
116	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
132 or 137	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
145 or 143	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40	ARNDT	95	DPWA	$\pi N \to N\pi$
44	HOEHLER	93	ARGD	$\pi N \to \pi N$
34 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
37	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
+ 1	ARNDT	95	DPWA	$\pi N \to N\pi$
−17	HOEHLER	93	ARGD	$\pi N \to \pi N$
-25 ± 5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−14	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1680)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	
Γ_3	ΛK	
Γ_4	ΣK	
Γ_5	$N\pi\pi$	30–40 %
Γ_6	$\Delta\pi$	5–15 %
Γ_7	$\Delta(1232)\pi$, P-wave	6–14 %
Γ_8	$\Delta(1232)\pi$, F-wave	<2 %
Γ_9	$N\rho$	3–15 %
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\rho$, S=3/2, P-wave	<12 %
Γ_{12}	$N\rho$, S=3/2, F-wave	1–5 %
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %
Γ_{14}	$p\gamma$	0.21–0.32 %
Γ_{15}	$p\gamma$, helicity=1/2	0.001–0.011 %
Γ_{16}	$p\gamma$, helicity=3/2	0.20–0.32 %
Γ_{17}	$n\gamma$	0.021–0.046 %
Γ_{18}	$n\gamma$, helicity=1/2	0.004–0.029 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.024 %

$N(1680)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.7 OUR ESTIMATE				
0.70 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.62 ± 0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.65 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.68	ARNDT	95	DPWA	$\pi N \to N\pi$
0.69 ± 0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	BAKER	79	DPWA	$\pi^- p \to n\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.01 ± 0.004	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
0.0005 or 0.001	[5] CARRERAS	70	MPWA	t pole + resonance
0.0004	[5] BOTKE	69	MPWA	t pole + resonance
0.003 ± 0.002	[5] DEANS	69	MPWA	t pole + resonance

$\Gamma(N\eta)/\Gamma(N\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.027	HEUSCH	66	RVUE	π^0, η photoproduction

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

Coupling to ΛK not required in the analyses of BAKER 77, SAXON 80, or BELL 83.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.01	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
-0.009 ± 0.009	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.001	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.31 to −0.21 OUR ESTIMATE				
-0.26 ± 0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.27	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.25	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.38	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 to +0.11 OUR ESTIMATE				
$+0.07 \pm 0.03$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.07	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.08	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.05	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.30 to −0.10 OUR ESTIMATE				
-0.20 ± 0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.23	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, F-wave $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.18 to −0.10 OUR ESTIMATE				
-0.13 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.15	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25 to +0.35 OUR ESTIMATE				
$+0.29 \pm 0.04$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.31	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.42	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ PHOTON DECAY AMPLITUDES

$N(1680) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.015 ± 0.006 OUR ESTIMATE				
-0.010 ± 0.004	ARNDT	96	IPWA	$\gamma N \to \pi N$
-0.017 ± 0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.009 ± 0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.028 ± 0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.026 ± 0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.018 ± 0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.006 ± 0.002	LI	93	IPWA	$\gamma N \to \pi N$
-0.005 ± 0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.009 ± 0.002	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.133±0.012 OUR ESTIMATE				
0.145±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.132±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.115±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.115±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.122±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.141±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.154±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.138±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.121±0.010	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.029±0.010 OUR ESTIMATE				
0.030±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.017±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.032±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.026±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.028±0.014	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.044±0.012	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.025±0.010	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.037±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.033±0.009 OUR ESTIMATE				
−0.040±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.033±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.023±0.005	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.024±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.017	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.033±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.035±0.012	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.048±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.038±0.018	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The parametrization used may be double counting.

[6] The range given is from 3 of 4 best solutions; not present in solution 1. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1680)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)	
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)	
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)	
HOEHLER	93	πN Newsletter 9 1		(KARL)	
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)	
MANLEY	92	PR D45 4002	+Saleski	(KENT)	IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)	
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE)	IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL)	IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)	
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)	
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)	
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)	
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)	
ARAI	80	Toronto Conf. 93		(INUS)	
Also	82	NP B194 251	Arai, Fujii	(INUS)	
CRAWFORD	80	Toronto Conf. 107		(GLAS)	
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)	IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)	IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS)	IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)	
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL)	IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT)	IJP
Also	80	Toronto Conf. 3	Koch	(KARLT)	IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)	
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)	
NOVOSELLER	78	NP B137 509		(CIT)	IJP
Also	78B	NP B137 445	Novoseller	(CIT)	IJP
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL)	IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL)	IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL)	IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF)	I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK)	IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH)	IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)	
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL)	IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC)	IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)	
CARRERAS	70	NP B16 35	+Donnachie	(DARE, MCHS)	
BOTKE	69	PR 180 1417		(UCSB)	
DEANS	69	PR 185 1797	+Wooten	(SFLA)	
HEUSCH	66	PRL 17 1019	+Prescott, Dashen	(CIT)	

$N(1700)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

$N(1700)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650 to 1750 (≈ 1700) OUR ESTIMATE				
1737±44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1675±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1731±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1791±46	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1709	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1650	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1690 to 1710	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1719	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1670±10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1690	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1660	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1710	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 150 (≈ 100) OUR ESTIMATE				
250±220	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
90± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
110± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
215± 60	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
166	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
70	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
70 to 100	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
126	BARBOUR	78	DPWA	$\gamma N \to \pi N$
90± 25	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
100	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
600	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1730 (≈ 1680) OUR ESTIMATE				
1700	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1660±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1710 or 1678	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1616 or 1613	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 150 (≈ 100) OUR ESTIMATE				
120	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
90±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
607 or 567	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
577 or 575	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5	HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
6±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
0±50	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$N(1700)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	
Γ_3	ΛK	<3 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	85–95 %
Γ_6	$\Delta\pi$	
Γ_7	$\Delta(1232)\pi$, S-wave	
Γ_8	$\Delta(1232)\pi$, D-wave	
Γ_9	$N\rho$	<35 %
Γ_{10}	$N\rho$, $S=1/2$, D-wave	
Γ_{11}	$N\rho$, $S=3/2$, S-wave	
Γ_{12}	$N\rho$, $S=3/2$, D-wave	
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{14}	$p\gamma$	0.01–0.05 %
Γ_{15}	$p\gamma$, helicity=1/2	0.0–0.024 %
Γ_{16}	$p\gamma$, helicity=3/2	0.002–0.026 %
Γ_{17}	$n\gamma$	0.01–0.13 %
Γ_{18}	$n\gamma$, helicity=1/2	0.0–0.09 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.05 %

$N(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.01±0.02	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.11±0.05	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.08±0.03	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04±0.05	BATINIC	95	DPWA	$\pi N \rightarrow N\pi, N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10±0.06	BATINIC	95	DPWA	$\pi N \rightarrow N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06 to +0.04 OUR ESTIMATE				
−0.012	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
−0.012	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.04	[6] BAKER	78	DPWA	See SAXON 80
−0.03 ±0.004	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
−0.03	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
+0.026±0.019	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	LIVANOS	80	DPWA	$\pi p \rightarrow \Sigma K$
<0.017	[7] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00 to ±0.08 OUR ESTIMATE				
+0.02±0.03	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.16	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.04 to ±0.20 OUR ESTIMATE				
+0.10±0.09	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
−0.12	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.14	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow N\rho$, $S=3/2$, S-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.01 to ±0.13 OUR ESTIMATE				
−0.04±0.06	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
−0.07	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.07	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1700) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.02 to ±0.28 OUR ESTIMATE				
+0.02±0.02	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.2	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1700)$ PHOTON DECAY AMPLITUDES

$N(1700) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.018±0.013 OUR ESTIMATE				
−0.016±0.014	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
−0.002±0.013	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.028±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.029±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.024±0.019	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.033±0.021	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
−0.014±0.025	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1700) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.002±0.024 OUR ESTIMATE				
−0.009±0.012	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.029±0.014	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.002±0.005	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.014±0.005	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.017±0.014	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.014±0.025	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
0.0 ±0.014	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1700) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.000±0.050 OUR ESTIMATE				
0.006±0.024	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.002±0.013	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.052±0.030	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.055±0.030	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.052±0.035	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.050±0.042	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1700) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.003±0.044 OUR ESTIMATE				
−0.033±0.017	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.018±0.018	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.037±0.036	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.035±0.024	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.041±0.030	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.035±0.030	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1700)$ $\gamma p \rightarrow \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(1700) \rightarrow \Lambda K^+$ (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.09	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(1700) \rightarrow \Lambda K^+$ (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−7.09	TANABE	89	DPWA

$p\gamma \to N(1700) \to \Lambda K^+$ phase angle θ (E_{2-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−35.9	TANABE	89	DPWA

$N(1700)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[7] The range given is from the four best solutions.

$N(1700)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1710)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

$N(1710)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1680 to 1740 (≈ 1710) OUR ESTIMATE				
1717±28	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1700±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1723± 9	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1720±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1766±34	[1] BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1706	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1692	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1730	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1690	BAKER	79	DPWA	$\pi^- p \to n\eta$
1650 to 1680	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1721	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1625±10	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1650	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1720	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1670	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1710	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 100) OUR ESTIMATE				
480±230	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
93± 30	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
90± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120± 15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
105± 10	ARNDT	96	IPWA	$\gamma N \to \pi N$
185± 61	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
540	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
200	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
550	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
97	BAKER	79	DPWA	$\pi^- p \to n\eta$
90 to 150	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
167	BARBOUR	78	DPWA	$\gamma N \to \pi N$
160± 6	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
95	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
120	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
174	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
75	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1770 (≈ 1720) OUR ESTIMATE				
1770	ARNDT	95	DPWA	$\pi N \to N\pi$
1690	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
1698	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1690±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1636	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1708 or 1712	[6] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1720 or 1711	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 380 (≈ 230) OUR ESTIMATE				
378	ARNDT	95	DPWA	$\pi N \to N\pi$
200	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
88	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
80±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
544	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
17 or 22	[6] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
123 or 115	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
37	ARNDT	95	DPWA	$\pi N \to N\pi$
15	HOEHLER	93	SPED	$\pi N \to \pi N$
9	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
8±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−167	ARNDT	95	DPWA	$\pi N \to N\pi$
−167	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
175±35	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1710)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	5–25 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	40–90 %
Γ_6	$\Delta\pi$	15–40 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	5–25 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %
Γ_{12}	$p\gamma$	0.002–0.05%
Γ_{13}	$p\gamma$, helicity=1/2	0.002–0.05%
Γ_{14}	$n\gamma$	0.0–0.02%
Γ_{15}	$n\gamma$, helicity=1/2	0.0–0.02%

$N(1710)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.09±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.12±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08±0.14	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16±0.10	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.383	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.12 to +0.18 OUR ESTIMATE				
+0.16	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.14	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.12	[7] BAKER	78	DPWA	See SAXON 80
−0.05±0.03	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.10	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.10	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.075 to 0.203	[8] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.16 to ±0.22 OUR ESTIMATE				
−0.21±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.17	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.20	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to N\rho$, S=1/2, P-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.09 to ±0.19 OUR ESTIMATE				
+0.05±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.19	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.20	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.31	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1710) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.14 to ±0.22 OUR ESTIMATE				
+0.04±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.26	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.28	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ PHOTON DECAY AMPLITUDES

$N(1710) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.009±0.022 OUR ESTIMATE				
0.007±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.006±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.028±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.009±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.012±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.015±0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.037±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.001±0.039	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.053±0.019	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1710) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.002±0.014 OUR ESTIMATE				
−0.002±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.000±0.018	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.001±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.005±0.013	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.011±0.021	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.017±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.028±0.045	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1710)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \to N(1710) \to \Lambda K^+$ (M_{1-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−10.6 ±0.4	WORKMAN	90	DPWA
− 7.21	TANABE	89	DPWA

$p\gamma \to N(1710) \to \Lambda K^+$ phase angle θ (M_{1-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
215 ±3	WORKMAN	90	DPWA
176.3	TANABE	89	DPWA

$N(1710)$ FOOTNOTES

[1] BATINIC 95 finds a second state with a 6 MeV mass difference.

[2] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[3] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[5] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[6] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[7] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[8] The range given for DEANS 75 is from the four best solutions.

$N(1710)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	90	PR D42 235	+Wang	(CMU)
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1720)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1720)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1650 to 1750 (≈ 1720) OUR ESTIMATE				
1717±31	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1700±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1710±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1713±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1820	ARNDT	95	DPWA	$\pi N \to N\pi$
1711±26	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1720	LI	93	IPWA	$\gamma N \to \pi N$
1785	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1690	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1710 to 1790	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1809	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1640±10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1710	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1750	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1850	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1720	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
100 to 200 (≈ 150) OUR ESTIMATE				
380±180	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
125± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
153± 15	ARNDT	96	IPWA	$\gamma N \to \pi N$
354	ARNDT	95	DPWA	$\pi N \to N\pi$
235± 51	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
200	LI	93	IPWA	$\gamma N \to \pi N$
308	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
447	BAKER	79	DPWA	$\pi^- p \to n\eta$
300 to 400	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
285	BARBOUR	78	DPWA	$\gamma N \to \pi N$
200± 50	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
500	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
327	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1650 to 1750 (≈ 1700) OUR ESTIMATE				
1717	ARNDT	95	DPWA	$\pi N \to N\pi$
1686	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1680±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1675	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1716 or 1716	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1745 or 1748	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
110 to 390 (≈ 250) OUR ESTIMATE				
388	ARNDT	95	DPWA	$\pi N \to N\pi$
187	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
120±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
124 or 126	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
135 or 123	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
39	ARNDT	95	DPWA	$\pi N \to N\pi$
15	HOEHLER	93	SPED	$\pi N \to \pi N$
8±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
− 70	ARNDT	95	DPWA	$\pi N \to N\pi$
−160±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−130	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1720)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	1–15 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	>70 %
Γ_6	$\Delta\pi$	
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	70–85 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{12}	$p\gamma$	0.003–0.10 %
Γ_{13}	$p\gamma$, helicity=1/2	0.003–0.08 %
Γ_{14}	$p\gamma$, helicity=3/2	0.001–0.03 %
Γ_{15}	$n\gamma$	0.002–0.39 %
Γ_{16}	$n\gamma$, helicity=1/2	0.0–0.002 %
Γ_{17}	$n\gamma$, helicity=3/2	0.001–0.39 %

$N(1720)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10 to 0.20 OUR ESTIMATE				
0.13±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.10±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16	ARNDT	95	DPWA	$\pi N \to N\pi$
0.18±0.04	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.002±0.01	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.08	BAKER 79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.14 to −0.06 OUR ESTIMATE			
−0.09	BELL 83	DPWA	$\pi^- p \to \Lambda K^0$
−0.11	SAXON 80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.09	[6] BAKER 78	DPWA	See SAXON 80
−0.06±0.02	[1] BAKER 77	IPWA	$\pi^- p \to \Lambda K^0$
−0.09	[1] BAKER 77	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.051 to 0.087	[7] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Delta(1232)\pi$, *P*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
±0.27 to ±0.37 OUR ESTIMATE			
−0.17	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, S=1/2, *P*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.34±0.05	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.26	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.40	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, S=3/2, *P*-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.15	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.19	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

N(1720) PHOTON DECAY AMPLITUDES

$N(1720) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.018±0.030 OUR ESTIMATE			
−0.015±0.015	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.044±0.066	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.004±0.007	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.051±0.009	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.071±0.010	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.038±0.050	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.012±0.003	LI 93	IPWA	$\gamma N \to \pi N$
+0.111±0.047	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1720) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.019±0.020 OUR ESTIMATE			
0.007±0.010	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.024±0.006	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.040±0.016	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.058±0.010	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.011±0.011	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.014±0.040	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.022±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.063±0.032	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.001±0.015 OUR ESTIMATE			
0.007±0.015	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.002±0.005	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.019±0.033	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.001±0.038	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.003±0.034	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.050±0.004	LI 93	IPWA	$\gamma N \to \pi N$
+0.007±0.020	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.029±0.061 OUR ESTIMATE			
−0.005±0.025	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.015±0.019	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.139±0.039	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.134±0.044	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.018±0.028	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.017±0.004	LI 93	IPWA	$\gamma N \to \pi N$
+0.051±0.051	BARBOUR 78	DPWA	$\gamma N \to \pi N$

N(1720) $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ (E_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
10.2 ±0.2	WORKMAN 90	DPWA
9.52	TANABE 89	DPWA

$p\gamma \to N(1720) \to \Lambda K^+$ phase angle θ (E_{1+} amplitude)

VALUE (degrees)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
−124 ±2	WORKMAN 90	DPWA
−103.4	TANABE 89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ (M_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
−4.5 ±0.2	WORKMAN 90	DPWA
3.18	TANABE 89	DPWA

N(1720) FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The overall phase of BAKER 78 copulings has been changed to agree with previous conventions.

[7] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

N(1720) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1900)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: $**$

OMITTED FROM SUMMARY TABLE

N(1900) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1900 OUR ESTIMATE				
1879±17	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
498±78	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N\rho$, $S=1/2$, P-wave

N(1900) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.26±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1900) \to N\rho$, $S=1/2$, P-wave **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.34±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) REFERENCES

MANLEY 92 PR D45 4002 +Saleski (KENT)
Also 84 PR D30 904 Manley, Arndt, Goradia, Teplitz (VPI)

$N(1990)$ F_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^+)$ Status: $**$

OMITTED FROM SUMMARY TABLE

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses do not agree very well with one another.

N(1990) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1990 OUR ESTIMATE				
2086± 28	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2018	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1970± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2005±150	HOEHLER	79	IPWA	$\pi N \to \pi N$
1999	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1990) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
535±120	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
295	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
350±120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
216	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1990) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1990) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−60±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1990) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2
Γ_8	$n\gamma$, helicity=1/2
Γ_9	$n\gamma$, helicity=3/2

N(1990) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1990) \to N\eta$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1990) \to \Lambda K$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
−0.021±0.033	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1990) \to \Sigma K$ **$(\Gamma_1\Gamma_4)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
0.010 to 0.023	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.06	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 1)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1990) \to N\pi\pi$ **$(\Gamma_1\Gamma_5)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1990) PHOTON DECAY AMPLITUDES

$N(1990) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.030±0.029	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.001±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.040	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.086±0.060	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004±0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.004	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.001	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.078±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.069	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.178	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.116±0.045	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.072	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

$N(1990)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$N(2000)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Older results have been retained simply because there is little information at all about this possible state.

$N(2000)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2000 OUR ESTIMATE				
1903±87	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1882±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2025	AYED	76	IPWA	$\pi N \to \pi N$
1970	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
2175	ALMEHED	72	IPWA	$\pi N \to \pi N$
1930	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1814	ARNDT	95	DPWA	$\pi N \to N\pi$

$N(2000)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
490±310	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
95± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
157	AYED	76	IPWA	$\pi N \to \pi N$
170	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
150	ALMEHED	72	IPWA	$\pi N \to \pi N$
112	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
176	ARNDT	95	DPWA	$\pi N \to N\pi$

$N(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, P-wave
Γ_7	$N\rho$, S=3/2, P-wave
Γ_8	$N\rho$, S=3/2, F-wave
Γ_9	$p\gamma$

$N(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.08±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08	AYED	76	IPWA	$\pi N \to \pi N$
0.25	ALMEHED	72	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10	ARNDT	95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.03	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.022	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.05	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.10±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.22±0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.11±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \to N(2000) \to \Lambda K$ $(\Gamma_9\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.0022	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ FOOTNOTES

[1] Not seen in solution 1 of LANGBEIN 73.
[2] Value given is from solution 1 of DEANS 75; not present in solutions 2, 3, or 4.

$N(2000)$ REFERENCES

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
AYED	76	Thesis CEA-N-1921		(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP
ALMEHED	72	NP B40 157	+Lovelace	(LUND, RUTG) IJP
DEANS	72	PR D6 1906	+Jacobs, Lyons, Montgomery	(SFLA) IJP

$N(2080)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is some evidence for two resonances in this wave between 1800 and 2200 MeV (see CUTKOSKY 80). However, the solution of HOEHLER 79 is quite different.

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(2080)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2080 OUR ESTIMATE				
1804± 55	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1920	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2060± 80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1900	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2081± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1986± 75	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1880	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2080)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
450±185	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
320	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
180± 60	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
300±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
240	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
265± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1050±225	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
87	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2080)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880 ± 100	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (lower m)
$2050\pm\ 70$	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

$-2\times$IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
160 ± 80	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (lower m)
200 ± 80	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

$N(2080)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$10\pm\ 5$	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (lower m)
30 ± 20	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (higher m)

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
$100\pm\ 80$	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (lower m)
0 ± 100	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (higher m)

$N(2080)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, S-wave
Γ_7	$\Delta(1232)\pi$, D-wave
Γ_8	$N\rho$, S=3/2, S-wave
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$
Γ_{10}	$p\gamma$, helicity=1/2
Γ_{11}	$p\gamma$, helicity=3/2
Γ_{12}	$n\gamma$, helicity=1/2
Γ_{13}	$n\gamma$, helicity=3/2
Γ_{14}	$p\gamma$

$N(2080)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.23 ± 0.03	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.10 ± 0.04	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (lower m)
0.14 ± 0.07	[1] CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$ (higher m)
0.06 ± 0.02	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.09 ± 0.02	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07 ± 0.04	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.065	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.04$	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
$+0.03$	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.014 to 0.037	[2] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.09	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.22\pm0.07$	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow N\rho$, S=3/2, S-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.24 ± 0.06	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(2080) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.25\pm0.06$	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(2080) \rightarrow N\eta$ $(\Gamma_{14}\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037	HICKS	73	MPWA	$\gamma p \rightarrow p\eta$

$N(2080)$ PHOTON DECAY AMPLITUDES

$N(2080) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.020 ± 0.008	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.026 ± 0.052	DEVENISH	74	DPWA	$\gamma N \rightarrow \pi N$

$N(2080) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.017 ± 0.011	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.128 ± 0.057	DEVENISH	74	DPWA	$\gamma N \rightarrow \pi N$

$N(2080) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.007 ± 0.013	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.053 ± 0.083	DEVENISH	74	DPWA	$\gamma N \rightarrow \pi N$

$N(2080) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.053 ± 0.034	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.100 ± 0.141	DEVENISH	74	DPWA	$\gamma N \rightarrow \pi N$

$N(2080)$ $\gamma p \rightarrow \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(2080) \rightarrow \Lambda K^+$ (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$5.5\ \pm0.3$	WORKMAN	90	DPWA
4.09	TANABE	89	DPWA

$p\gamma \rightarrow N(2080) \rightarrow \Lambda K^+$ phase angle θ (E_{2-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$-48\ \pm5$	WORKMAN	90	DPWA
-35.9	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(2080) \rightarrow \Lambda K^+$ (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$-6.7\ \pm0.2$	WORKMAN	90	DPWA
-4.09	TANABE	89	DPWA

$N(2080)$ FOOTNOTES

[1] CUTKOSKY 80 finds a lower mass D_{13} resonance, as well as one in this region. Both are listed here.

[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2080)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
DEVENISH	74	PL 52B 227	+Lyth, Rankin	(DESY, LANC, BONN) IJP
HICKS	73	PR D7 2614	+Deans, Jacobs, Lyons+	(CMU, ORNL, SFLA) IJP

$N(2090)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: $*$

OMITTED FROM SUMMARY TABLE

Any structure in the S_{11} wave above 1800 MeV is listed here. A few early results that are now obsolete have been omitted.

$N(2090)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2090 OUR ESTIMATE				
1928±59	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2180±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1880±20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
414±157	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
95± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2150±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1937 or 1949	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 or 131	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$N(2090)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
40±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
0±90	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2090)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΛK
Γ_3	$N\pi\pi$

$N(2090)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10±0.10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18±0.08	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.09±0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2090) \to \Lambda K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2090)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$N(2090)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$N(2100)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $*$

OMITTED FROM SUMMARY TABLE

$N(2100)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2100 OUR ESTIMATE				
1885±30	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2125±75	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2050±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2203±70	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2100)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
113± 44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
260±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
200± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
418±171	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2100)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2120±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
240±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2100)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
14±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
35±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2100)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	$N\pi\pi$
Γ_4	$\Delta(1232)\pi$, P-wave

$N(2100)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.15±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11±0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.86±0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2100) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.19±0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$N(2100)$ REFERENCES

BATINIC 95 PR C51 2310 +Slaus, Svarc, Nefkens (BOSK, UCLA)
MANLEY 92 PR D45 4002 +Saleski (KENT) IJP
Also 84 PR D30 904 Manley, Arndt, Goradia, Teplitz (VPI)
ARNDT 91 PR D43 2131 +Li, Roper, Workman, Ford (VPI, TELE) IJP
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL)
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARLT) IJP
Also 80 Toronto Conf. 3 Koch (KARLT) IJP

$N(2190)$ G_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(2190)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 to 2200 (≈ 2190) OUR ESTIMATE				
2127± 9	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2200±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2140±12	HOEHLER	79	IPWA	$\pi N \to \pi N$
2140±40	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2131	ARNDT	95	DPWA	$\pi N \to N\pi$
2198±68	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
2098	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2180	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2140	BAKER	79	DPWA	$\pi^- p \to n\eta$
2117	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 to 550 (≈ 450) OUR ESTIMATE				
550± 50	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
500±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
390± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
270± 50	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
476	ARNDT	95	DPWA	$\pi N \to N\pi$
805±140	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
238	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
80	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
319	BAKER	79	DPWA	$\pi^- p \to n\eta$
220	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1950 to 2150 (≈ 2050) OUR ESTIMATE				
2030	ARNDT	95	DPWA	$\pi N \to N\pi$
2042	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
2100±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2060	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 to 550 (≈ 450) OUR ESTIMATE				
460	ARNDT	95	DPWA	$\pi N \to N\pi$
482	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
400±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
464	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2190)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
46	ARNDT	95	DPWA	$\pi N \to N\pi$
45	HOEHLER	93	SPED	$\pi N \to \pi N$
25±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
54	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−23	ARNDT	95	DPWA	$\pi N \to N\pi$
−30±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−44	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2190)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	
Γ_4	ΣK	
Γ_5	$N\pi\pi$	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$p\gamma$, helicity=1/2	
Γ_9	$p\gamma$, helicity=3/2	
Γ_{10}	$n\gamma$, helicity=1/2	
Γ_{11}	$n\gamma$, helicity=3/2	

$N(2190)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.22±0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.12±0.06	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.16±0.04	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.23	ARNDT	95	DPWA	$\pi N \to N\pi$
0.19±0.05	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.003	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.052	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.02	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.014 to 0.019	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.25±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$N(2190)$ PHOTON DECAY AMPLITUDES

$N(2190) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.055	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.180	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.042	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.085	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.126	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (E_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.5 ±1.0	WORKMAN	90	DPWA
2.04	TANABE	89	DPWA

$p\gamma \to N(2190) \to \Lambda K^+$ phase angle θ (E_{4-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
− 4 ±9	WORKMAN	90	DPWA
−27.5	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (M_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−7.0 ±0.7	WORKMAN	90	DPWA
−5.78	TANABE	89	DPWA

$N(2190)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2190)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$N(2200)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The mass is not well determined. A few early results have been omitted.

$N(2200)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
1900	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
2180±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1920	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2228±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2240±65	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2200)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
400±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
310± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
761±139	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
360±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
20±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−90±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK

$N(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08±0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.01	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(2200) \to N\eta$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.066	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(2200) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.03	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.05	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

N(2200) REFERENCES

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$N(2220)$ H_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(2220) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2180 to 2310 (≈ 2220) OUR ESTIMATE			
2230± 80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
2205± 10	HOEHLER 79	IPWA	$\pi N \to \pi N$
2300±100	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2258	ARNDT 95	DPWA	$\pi N \to N\pi$
2050	BAKER 79	DPWA	$\pi^- p \to n\eta$

N(2220) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
320 to 550 (≈ 400) OUR ESTIMATE			
500±150	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
365± 30	HOEHLER 79	IPWA	$\pi N \to \pi N$
450±150	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
334	ARNDT 95	DPWA	$\pi N \to N\pi$

N(2220) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2100 to 2240 (≈ 2170) OUR ESTIMATE			
2203	ARNDT 95	DPWA	$\pi N \to N\pi$
2135	[1] HOEHLER 93	ARGD	$\pi N \to \pi N$
2160±80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2253	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
370 to 570 (≈ 470) OUR ESTIMATE			
536	ARNDT 95	DPWA	$\pi N \to N\pi$
400	[1] HOEHLER 93	ARGD	$\pi N \to \pi N$
480±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
640	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2220) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
68	ARNDT 95	DPWA	$\pi N \to N\pi$
40	HOEHLER 93	ARGD	$\pi N \to \pi N$
45±20	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
85	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID	TECN	COMMENT
−43	ARNDT 95	DPWA	$\pi N \to N\pi$
−50	HOEHLER 93	ARGD	$\pi N \to \pi N$
−45±25	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−62	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2220) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	

N(2220) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE			
0.15±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.18±0.015	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.12±0.04	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.26	ARNDT 95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2220) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.034	BAKER 79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2220) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
not required	BELL 83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON 80	DPWA	$\pi^- p \to \Lambda K^0$

N(2220) FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

N(2220) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2250)$ G_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$ Status: ∗∗∗∗

N(2250) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2170 to 2310 (≈ 2250) OUR ESTIMATE			
2250± 80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
2268± 15	HOEHLER 79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2291	ARNDT 95	DPWA	$\pi N \to N\pi$

N(2250) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
290 to 470 (≈ 400) OUR ESTIMATE			
480±120	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
300± 40	HOEHLER 79	IPWA	$\pi N \to \pi N$
350±100	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
772	ARNDT 95	DPWA	$\pi N \to N\pi$

N(2250) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2080 to 2200 (≈ 2140) OUR ESTIMATE			
2087	ARNDT 95	DPWA	$\pi N \to N\pi$
2187	[1] HOEHLER 93	SPED	$\pi N \to \pi N$
2150±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2243	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
280 to 680 (≈ 480) OUR ESTIMATE			
680	ARNDT 95	DPWA	$\pi N \to N\pi$
388	[1] HOEHLER 93	SPED	$\pi N \to \pi N$
360±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
650	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2250)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
24	ARNDT 95	DPWA	$\pi N \to N\pi$
21	HOEHLER 93	SPED	$\pi N \to \pi N$
20±6	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
47	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID	TECN	COMMENT
−44	ARNDT 95	DPWA	$\pi N \to N\pi$
−50±20	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−37	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2250)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	
Γ_3	ΛK	

$N(2250)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE			
0.10±0.02	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.10±0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.09±0.02	HENDRY 78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.10	ARNDT 95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(2250) \to N\eta$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.043	BAKER 79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to N(2250) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.02	BELL 83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON 80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2250)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

$N(2250)$ REFERENCES

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2600)$ $I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$ Status: ∗∗∗

$N(2600)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2550 to 2750 (≈ 2600) OUR ESTIMATE			
2577± 50	HOEHLER 79	IPWA	$\pi N \to \pi N$
2700±100	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2600)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
500 to 800 (≈ 650) OUR ESTIMATE			
400±100	HOEHLER 79	IPWA	$\pi N \to \pi N$
900±100	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–10 %

$N(2600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.1 OUR ESTIMATE			
0.05±0.01	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.08±0.02	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2600)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2700)$ $K_{1,13}$

$I(J^P) = \frac{1}{2}(\frac{13}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$N(2700)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2700 OUR ESTIMATE			
2612± 45	HOEHLER 79	IPWA	$\pi N \to \pi N$
3000±100	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2700)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
350± 50	HOEHLER 79	IPWA	$\pi N \to \pi N$
900±150	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2700)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(2700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.04±0.01	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.07±0.02	HENDRY 78	MPWA	$\pi N \to \pi N$

$N(2700)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-1/2 resonances found in partial-wave analyses.

Our 1982 edition had an $N(3245)$, an $N(3690)$, and an $N(3755)$, each a narrow peak seen in a production experiment. Since nothing has been heard from them since the 1960's, we declare them to be dead. There was also an $N(3030)$, deduced from total cross-section and 180° elastic cross-section measurements; it is the KOCH 80 $L_{1,15}$ state below.

$N(\sim 3000)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 3000 OUR ESTIMATE				
2600	KOCH	80	IPWA	$\pi N \to \pi N\ D_{13}$
3100	KOCH	80	IPWA	$\pi N \to \pi N\ L_{1,15}$ wave
3500	KOCH	80	IPWA	$\pi N \to \pi N\ M_{1,17}$ wave
3500 to 4000	KOCH	80	IPWA	$\pi N \to \pi N\ N_{1,19}$ wave
3500±200	HENDRY	78	MPWA	$\pi N \to \pi N\ L_{1,15}$ wave
3800±200	HENDRY	78	MPWA	$\pi N \to \pi N\ M_{1,17}$ wave
4100±200	HENDRY	78	MPWA	$\pi N \to \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1300±200	HENDRY	78	MPWA	$\pi N \to \pi N\ L_{1,15}$ wave
1600±200	HENDRY	78	MPWA	$\pi N \to \pi N\ M_{1,17}$ wave
1900±300	HENDRY	78	MPWA	$\pi N \to \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.055±0.02	HENDRY	78	MPWA	$\pi N \to \pi N\ L_{1,15}$ wave
0.040±0.015	HENDRY	78	MPWA	$\pi N \to \pi N\ M_{1,17}$ wave
0.030±0.015	HENDRY	78	MPWA	$\pi N \to \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND) IJP

Δ BARYONS
$(S = 0, I = 3/2)$

$\Delta^{++} = uuu, \quad \Delta^{+} = uud, \quad \Delta^{0} = udd, \quad \Delta^{-} = ddd$

$\Delta(1232)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1977 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1232)$ BREIT-WIGNER MASSES

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1230 to 1234 (≈ 1232) OUR ESTIMATE				
1231±1	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1232±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1233±2	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1233	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$

$\Delta(1232)^{++}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1230.5±0.2	ABAEV	95	IPWA	$\pi N \rightarrow \pi N$
1230.9±0.3	KOCH	80B	IPWA	$\pi N \rightarrow \pi N$
1231.1±0.2	PEDRONI	78		$\pi N \rightarrow \pi N$ 70–370 MeV

$\Delta(1232)^{+}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1231.6	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1234.9±1.4	MIROSHNIC...	79		Fit photoproduction
1231.2	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1231.8	BERENDS	75	IPWA	$\gamma p \rightarrow \pi N$

$\Delta(1232)^{0}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1233.1±0.3	ABAEV	95	IPWA	$\pi N \rightarrow \pi N$
1233.6±0.5	KOCH	80B	IPWA	$\pi N \rightarrow \pi N$
1233.8±0.2	PEDRONI	78		$\pi N \rightarrow \pi N$ 70–370 MeV

$m_{\Delta^0} - m_{\Delta^{++}}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.25±0.68	BERNICHA	96		Fit to PEDRONI 78
2.6 ±0.4	ABAEV	95	IPWA	$\pi N \rightarrow \pi N$
2.7 ±0.3	[1] PEDRONI	78		See the masses

$\Delta(1232)$ BREIT-WIGNER WIDTHS

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
115 to 125 (≈ 120) OUR ESTIMATE				
118±4	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
120±5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
116±5	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$

$\Delta(1232)^{++}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
111.0±1.0	KOCH	80B	IPWA	$\pi N \rightarrow \pi N$
111.3±0.5	PEDRONI	78		$\pi N \rightarrow \pi N$ 70–370 MeV

$\Delta(1232)^{+}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
111.2	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
131.1±2.4	MIROSHNIC...	79		Fit photoproduction
111.0	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1232)^{0}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
113.0±1.5	KOCH	80B	IPWA	$\pi N \rightarrow \pi N$
117.9±0.9	PEDRONI	78		$\pi N \rightarrow \pi N$ 70–370 MeV

Δ^0-Δ^{++} WIDTH DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
8.45±1.11	BERNICHA	96		Fit to PEDRONI 78
5.1 ±1.0	ABAEV	95	IPWA	$\pi N \rightarrow \pi N$
6.6 ±1.0	PEDRONI	78		See the widths

$\Delta(1232)$ POLE POSITIONS

REAL PART, MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1209 to 1211 (≈ 1210) OUR ESTIMATE				
1211	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1209	[2] HOEHLER	93	ARGD	$\pi N \rightarrow \pi N$
1210±1	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

−2×IMAGINARY PART, MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
98 to 102 (≈ 100) OUR ESTIMATE				
100	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
100	[2] HOEHLER	93	ARGD	$\pi N \rightarrow \pi N$
100±2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

REAL PART, $\Delta(1232)^{++}$

VALUE (MeV)	*DOCUMENT ID*		*COMMENT*
1209.6±0.5	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1210.5 to 1210.8	[4] VASAN	76B	Fit to CARTER 73

−2×IMAGINARY PART, $\Delta(1232)^{++}$

VALUE (MeV)	*DOCUMENT ID*		*COMMENT*
100.8±1.0	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
99.8 to 100	[4] VASAN	76B	Fit to CARTER 73

REAL PART, $\Delta(1232)^{+}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1208.0±2.0	CAMPBELL	76		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1211 ±1 to 1212 ± 1	HANSTEIN	96	DPWA	$\gamma N \rightarrow \pi N$
1206.9±0.9 to 1210.5 ± 1.8	MIROSHNIC...	79		Fit photoproduction

−2×IMAGINARY PART, $\Delta(1232)^{+}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
106 ±4	CAMPBELL	76		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
102 ±2 to 99 ± 2	HANSTEIN	96	DPWA	$\gamma N \rightarrow \pi N$
111.2±2.0 to 116.6 ± 2.2	MIROSHNIC...	79		Fit photoproduction

REAL PART, $\Delta(1232)^{0}$

VALUE (MeV)	*DOCUMENT ID*		*COMMENT*
1210.75±0.6	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1210.2	[4] VASAN	76B	Fit to CARTER 73

−2×IMAGINARY PART, $\Delta(1232)^{0}$

VALUE (MeV)	*DOCUMENT ID*		*COMMENT*
105.6±1.2	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
105.8 to 106.2	[4] VASAN	76B	Fit to CARTER 73

$\Delta(1232)$ ELASTIC POLE RESIDUES

ABSOLUTE VALUE, MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
38	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
50	HOEHLER	93	ARGD	$\pi N \rightarrow \pi N$
53±2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
52	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE, MIXED CHARGES

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−22	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
−48	HOEHLER	93	ARGD	$\pi N \rightarrow \pi N$
−47±1	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−31	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

ABSOLUTE VALUE, $\Delta(1232)^{++}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
52.4 to 53.2	[3] VASAN	76B	Fit to CARTER 73
52.1 to 52.4	[4] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^{++}$

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.822 to −0.833	[3] VASAN	76B	Fit to CARTER 73
−0.823 to −0.830	[4] VASAN	76B	Fit to CARTER 73

ABSOLUTE VALUE, $\Delta(1232)^{0}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
54.8 to 55.0	[3] VASAN	76B	Fit to CARTER 73
55.2 to 55.3	[4] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^{0}$

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.840 to −0.847	[3] VASAN	76B	Fit to CARTER 73
−0.848 to −0.856	[4] VASAN	76B	Fit to CARTER 73

$\Delta(1232)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	>99 %
Γ_2	$N\gamma$	0.52–0.60 %
Γ_3	$N\gamma$, helicity=1/2	0.11–0.13 %
Γ_4	$N\gamma$, helicity=3/2	0.41–0.47 %

$\Delta(1232)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.993 to 0.995 OUR ESTIMATE				
1.0	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1.0	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1.0	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$

$\Delta(1232)$ PHOTON DECAY AMPLITUDES

$\Delta(1232) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.135 ±0.006 OUR ESTIMATE				
−0.135 ±0.005	ARNDT	97	IPWA	$\gamma N \rightarrow \pi N$
−0.1278±0.0012	DAVIDSON	97	DPWA	$\gamma N \rightarrow \pi N$
−0.132 ±0.002	TIATOR	97	DPWA	$\gamma N \rightarrow \pi N$
−0.141 ±0.005	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.135 ±0.016	DAVIDSON	91B	FIT	$\gamma N \rightarrow \pi N$
−0.145 ±0.015	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
−0.138 ±0.004	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.147 ±0.001	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.145 ±0.001	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.136 ±0.006	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.143 ±0.004	LI	93	IPWA	$\gamma N \rightarrow \pi N$
−0.140 ±0.007	DAVIDSON	90	FIT	See DAVIDSON 91B
−0.142 ±0.007	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
−0.140	[5] NOELLE	78		$\gamma N \rightarrow \pi N$
−0.141 ±0.004	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1232) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.255 ±0.008 OUR ESTIMATE				
−0.250 ±0.008	ARNDT	97	IPWA	$\gamma N \rightarrow \pi N$
−0.2524±0.0013	DAVIDSON	97	DPWA	$\gamma N \rightarrow \pi N$
−0.253 ±0.003	TIATOR	97	DPWA	$\gamma N \rightarrow \pi N$
−0.261 ±0.005	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.251 ±0.033	DAVIDSON	91B	FIT	$\gamma N \rightarrow \pi N$
−0.263 ±0.026	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
−0.259 ±0.006	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.264 ±0.002	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.261 ±0.002	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.247 ±0.010	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.262 ±0.004	LI	93	IPWA	$\gamma N \rightarrow \pi N$
−0.254 ±0.011	DAVIDSON	90	FIT	See DAVIDSON 91B
−0.271 ±0.010	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
−0.247	[5] NOELLE	78		$\gamma N \rightarrow \pi N$
−0.256 ±0.003	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1232) \rightarrow N\gamma$, E_2/M_1 ratio

VALUE	DOCUMENT ID		TECN	COMMENT
−0.025 ±0.005 OUR ESTIMATE				
−0.015 ±0.005	[6] ARNDT	97	IPWA	$\gamma N \rightarrow \pi N$
−0.025 ±0.002 ±0.002	BECK	97	IPWA	$\gamma N \rightarrow \pi N$
−0.030 ±0.003 ±0.002	BLANPIED	97	DPWA	$\gamma N \rightarrow \pi N, \gamma N$
−0.0319±0.0024	DAVIDSON	97	DPWA	$\gamma N \rightarrow \pi N$
−0.025 ±0.001	TIATOR	97	DPWA	$\gamma N \rightarrow \pi N$
−0.015 ±0.005	WORKMAN	92	IPWA	$\gamma N \rightarrow \pi N$
−0.0157±0.0072	DAVIDSON	91B	FIT	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.027 ±0.003 ±0.001	KHANDAKER	95	DPWA	$\gamma N \rightarrow \pi N$
−0.0107±0.0037	DAVIDSON	90	FIT	$\gamma N \rightarrow \pi N$
−0.015 ±0.002	DAVIDSON	86	FIT	$\gamma N \rightarrow \pi N$
+0.037 ±0.004	TANABE	85	FIT	$\gamma N \rightarrow \pi N$

$\Delta(1232) \rightarrow N\gamma$, absolute value of E_2/M_1 ratio at pole

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.065±0.007	ARNDT	97	DPWA	$\gamma N \rightarrow \pi N$
−0.058	HANSTEIN	96	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1232) \rightarrow N\gamma$, phase of E_2/M_1 ratio at pole

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−122 ±5	ARNDT	97	DPWA	$\gamma N \rightarrow \pi N$
−127.2	HANSTEIN	96	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1232)^{++}$ MAGNETIC MOMENT

The values are extracted from UCLA and SIN data on $\pi^+ p$ bremsstrahlung using a variety of different theoretical approximations and methods. Our estimate is *only* a rough guess of the range we expect the moment to lie within.

VALUE (μ_N)	DOCUMENT ID		COMMENT
3.7 to 7.5 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.52±0.50±0.45	BOSSHARD	91	$\pi^+ p \rightarrow \pi^+ p\gamma$ (SIN data)
3.7 to 4.2	LIN	91B	$\pi^+ p \rightarrow \pi^+ p\gamma$ (from UCLA data)
4.6 to 4.9	LIN	91B	$\pi^+ p \rightarrow \pi^+ p\gamma$ (from SIN data)
5.6 to 7.5	WITTMAN	88	$\pi^+ p \rightarrow \pi^+ p\gamma$ (from UCLA data)
6.9 to 9.8	HELLER	87	$\pi^+ p \rightarrow \pi^+ p\gamma$ (from UCLA data)
4.7 to 6.7	NEFKENS	78	$\pi^+ p \rightarrow \pi^+ p\gamma$ (UCLA data)

$\Delta(1232)$ FOOTNOTES

[1] Using $\pi^{\pm} d$ as well, PEDRONI 78 determine $(M^- - M^{++}) + (M^0 - M^+)/3 = 4.6 \pm 0.2$ MeV.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] This VASAN 76B value is from fits to the coulomb-barrier-corrected CARTER 73 phase shift.

[4] This VASAN 76B value is from fits to the CARTER 73 nuclear phase shift without coulomb barrier corrections.

[5] Converted to our conventions using $M = 1232$ MeV, $\Gamma = 110$ MeV from NOELLE 78.

[6] This ARNDT 97 value is very sensitive to the database being fitted. The result is from a fit to the full pion photoproduction database, apart from the BLANPIED 97 cross-section measurements.

$\Delta(1232)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	97	PR C56 577	+Strakovsky, Workman	(VPI)
BECK	97	PRL 78 606	+Krahn+	(MANZ, SACL, PAVI, GLAS)
Also	97B	PRL 79 4510	Beck, Krahn	(MANZ)
Also	97C	PRL 79 4512	Beck, Krahn	(MANZ)
Also	97D	PRL 79 4515 (erratum)	Beck, Krahn+	(MANZ, SACL, PAVI, GLAS)
BLANPIED	97	PRL 79 4337	+Blecher, Caracappa+	(LEGS Collab.)
DAVIDSON	97	PRL 79 4509	+Mukhopadhyay	(RPI)
TIATOR	97	πN Newsletter 13, 127		(MANZ)
ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
BERNICHA	96	NP A597 623	+Lopez Castro, Pestieau	(LOUV, CINV)
HANSTEIN	96	PL B385 45	+Drechsel, Tiator	(MANZ)
ABAEV	95	ZPHY A352 85	+Kruglov	(PNPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
KHANDAKER	95	PR D51 3966	+Sandorfi	(BNL, VPI)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
WORKMAN	92	PR C46 1546	+Arndt, Li	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BOSSHARD	91	PR D44 1962	+Amsler+	(ZURI, LBL, VILL, LAUS, UCLA, CATH)
Also	90	PRL 64 2619	Bosshard+	(CATH, LAUS, LBL, VILL, UCLA, ZURI)
DAVIDSON	91B	PR D43 71	+Mukhopadhyay, Wittman	(RPI)
LIN	91B	PR C44 1819	+Liou, Ding	(CUNY, CSOK)
Also	91	PR C43 R930	Lin, Liou	(CUNY)
DAVIDSON	90	PR D42 20	+Mukhopadhyay	(RPI)
WITTMAN	88	PR C37 2075		(TRIU)

HELLER	87	PR C35 718	+Kumano, Martinez, Moniz	(LANL, MIT, ILL)
DAVIDSON	86	PRL 56 804	+Mukhopadhyay, Wittman	(RPI)
TANABE	85	PR C31 1876	+Ohta	(KOMAB)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
KOCH	80B	NP A336 331	+Pietarinen	(KARLT) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
MIROSHNIC...	79	SJNP 29 94 Translated from YAF 29 188.	Miroshnichenko, Nikiforov, Sanin+	(KFTI) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NEFKENS	78	PR D18 3911	+Arman, Ballagh, Glodis, Haddock+	(UCLA, CATH) IJP
NOELLE	78	PTP 60 778		(NAGO)
PEDRONI	78	NP A300 321	+Gabathuler, Domingo, Hirt+	(SIN, ISNG, KARLE+) IJP
CAMPBELL	76	PR D14 2431	+Shaw, Ball	(BOIS, UCI, UTAH) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
VASAN	76B	NP B106 535		(CMU) IJP
Also	76	NP B106 526	Vasan	(CMU) IJP
BERENDS	75	NP B84 342	+Donnachie	(LEID, MCHS)
CARTER	73	NP B58 378	+Bugg, Carter	(CAVE, LOQM) IJP

$\Delta(1600)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

$\Delta(1600)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1550 to 1700 (≈ 1600) OUR ESTIMATE				
1706±10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1600±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1522±13	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1672±15	ARNDT	96	IPWA	$\gamma N \to \pi N$
1706	LI	93	IPWA	$\gamma N \to \pi N$
1690	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1560	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1640	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
250 to 450 (≈ 350) OUR ESTIMATE				
430± 73	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
315± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
215	LI	93	IPWA	$\gamma N \to \pi N$
250	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
180	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1500 to 1700 (≈ 1600) OUR ESTIMATE				
1675	ARNDT	95	DPWA	$\pi N \to N\pi$
1550	[3] HOEHLER	93	SPED	$\pi N \to \pi N$
1550±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1612	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1609 or 1610	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1541 or 1542	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 400 (≈ 300) OUR ESTIMATE				
386	ARNDT	95	DPWA	$\pi N \to N\pi$
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
230	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
323 or 325	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
178 or 178	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
52	ARNDT	95	DPWA	$\pi N \to N\pi$
17±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
16	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
+ 14	ARNDT	95	DPWA	$\pi N \to N\pi$
−150±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 73	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1600)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–25 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	75–90 %
Γ_4	$\Delta\pi$	40–70 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	<25 %
Γ_8	$N\rho$, S=1/2, P-wave	
Γ_9	$N\rho$, S=3/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, F-wave	
Γ_{11}	$N(1440)\pi$	10–35 %
Γ_{12}	$N(1440)\pi$, P-wave	
Γ_{13}	$N\gamma$	0.001–0.02 %
Γ_{14}	$N\gamma$, helicity=1/2	0.0–0.02 %
Γ_{15}	$N\gamma$, helicity=3/2	0.001–0.005 %

$\Delta(1600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10 to 0.25 OUR ESTIMATE				
0.12±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.21±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1600) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.36 to −0.28 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.006 to 0.042	[5] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.27 to +0.33 OUR ESTIMATE				
+0.29±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.24±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.34	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.15 to −0.03 OUR ESTIMATE				
−0.07	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1600) \to N\rho$, S=1/2, P-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.10	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1600) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.10	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1600) \rightarrow N(1440)\pi$, *P*-wave $(\Gamma_1\Gamma_{12})^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.15 to +0.23 OUR ESTIMATE				
+0.16±0.02	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
+0.23±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1600)$ PHOTON DECAY AMPLITUDES

$\Delta(1600) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.023±0.020 OUR ESTIMATE				
−0.018±0.015	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.039±0.030	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
−0.046±0.013	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.005±0.020	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.026±0.002	LI	93	IPWA	$\gamma N \rightarrow \pi N$
−0.200	[7] WADA	84	DPWA	Compton scattering
0.000±0.030	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
0.0 ±0.020	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1600) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.009±0.021 OUR ESTIMATE				
−0.025±0.015	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.013±0.014	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.025±0.031	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.009±0.020	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.016±0.002	LI	93	IPWA	$\gamma N \rightarrow \pi N$
0.023	WADA	84	DPWA	Compton scattering
0.000±0.045	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
0.0 ±0.015	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1600)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] LONGACRE 77 considers this coupling to be well determined.

[7] WADA 84 is inconsistent with other analyses — see the Note on N and Δ Resonances.

$\Delta(1600)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1620)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1620)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1615 to 1675 (≈ 1620) OUR ESTIMATE				
1672 ± 7	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1620 ±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1610 ± 7	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1672 ± 5	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
1617	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1669	LI	93	IPWA	$\gamma N \rightarrow \pi N$
1620	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
1712.8± 6.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
1786.7± 2.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
1657	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1662	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1580	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1600	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1620)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
120 to 180 (≈ 150) OUR ESTIMATE				
154 ±37	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
140 ±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
139 ±18	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
147 ± 8	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
108	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
184	LI	93	IPWA	$\gamma N \rightarrow \pi N$
120	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
228.3±18.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$ (lower mass)
30.0± 6.4	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$ (higher mass)
161	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
180	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
120	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
150	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1620)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1580 to 1620 (≈ 1600) OUR ESTIMATE				
1585	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1608	[4] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
1600±15	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1587	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1583 or 1583	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1575 or 1572	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
100 to 130 (≈ 115) OUR ESTIMATE				
104	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
116	[4] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
120±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
143 or 149	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
119 or 128	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1620)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
14	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
19	HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
15±2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−121	ARNDT	95	DPWA	$\pi N \to N\pi$
− 95	HOEHLER	93	SPED	$\pi N \to \pi N$
−110±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−125	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1620)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	20–30 %
Γ_2	$N\pi\pi$	70–80 %
Γ_3	$\Delta\pi$	30–60 %
Γ_4	$\Delta(1232)\pi$, D-wave	
Γ_5	$N\rho$	7–25 %
Γ_6	$N\rho$, S=1/2, S-wave	
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$N(1440)\pi$	
Γ_9	$N\gamma$	0.004–0.044 %
Γ_{10}	$N\gamma$, helicity=1/2	0.004–0.044 %

$\Delta(1620)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.09±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.25±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.35±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29	ARNDT	95	DPWA	$\pi N \to N\pi$
0.60	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
0.36	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.36 to −0.28 OUR ESTIMATE				
−0.24±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.33±0.06	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
−0.39	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N\rho$, S=1/2, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.12 to +0.22 OUR ESTIMATE				
+0.15±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.40±0.10	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.08	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.28	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.15 to −0.03 OUR ESTIMATE				
−0.06±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.13	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N(1440)\pi$ $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.11±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ PHOTON DECAY AMPLITUDES

$\Delta(1620) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.027±0.011 OUR ESTIMATE				
0.035±0.020	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.035±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.010±0.015	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.022±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.021±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.126±0.021	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.042±0.003	LI	93	IPWA	$\gamma N \to \pi N$
0.066	WADA	84	DPWA	Compton scattering
+0.034±0.028	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.005±0.016	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1620)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances at somewhat higher masses than other analyses. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] LONGACRE 77 considers this coupling to be well determined.

$\Delta(1620)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1700)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1700)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1770 (≈ 1700) OUR ESTIMATE				
1762 ±44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1710 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1680 ±70	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1690 ±15	ARNDT	96	IPWA	$\gamma N \to \pi N$
1680	ARNDT	95	DPWA	$\pi N \to N\pi$
1655	LI	93	IPWA	$\gamma N \to \pi N$
1650	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
$1718.4^{+13.1}_{-13.0}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1622	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1629	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1600	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1680	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 400 (≈ 300) OUR ESTIMATE				
600 ±250	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
280 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
230 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
285 ± 20	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
272	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
348	LI	93	IPWA	$\gamma N \rightarrow \pi N$
160	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
193.3± 26.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
209	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
216	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
240	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1620 to 1700 (≈ 1660) OUR ESTIMATE				
1655	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1651	[4] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
1675±25	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1646	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1681 or 1672	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1600 or 1594	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 250 (≈ 200) OUR ESTIMATE				
242	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
159	[4] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
220±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
208	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
245 or 241	[5] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
208 or 201	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
16	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
10	HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
13±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
13	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−12	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
−20±25	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−22	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

Δ(1700) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	80–90 %
Γ_4	$\Delta\pi$	30–60 %
Γ_5	$\Delta(1232)\pi$, S-wave	25–50 %
Γ_6	$\Delta(1232)\pi$, D-wave	1–7 %
Γ_7	$N\rho$	30–55 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	5–20 %
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\gamma$	0.12–0.26 %
Γ_{12}	$N\gamma$, helicity=1/2	0.08–0.16 %
Γ_{13}	$N\gamma$, helicity=3/2	0.025–0.12 %

Δ(1700) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.14±0.06	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.20±0.03	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
0.16	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Sigma K$ $\qquad(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.002	LIVANOS	80	DPWA	$\pi p \rightarrow \Sigma K$
0.001 to 0.011	[6] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Delta(1232)\pi$, S-wave $\qquad(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.21 to +0.29 OUR ESTIMATE				
+0.32±0.06	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
+0.18±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
+0.30	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.24	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Delta(1232)\pi$, D-wave $\qquad(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.05 to +0.11 OUR ESTIMATE				
+0.08±0.03	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.14±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
+0.05	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.10	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=1/2, D-wave $\qquad(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.17±0.05	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, S-wave $\qquad(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.11 to ±0.19 OUR ESTIMATE				
+0.10±0.03	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
+0.04	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.30	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, D-wave $\qquad(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.07	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) PHOTON DECAY AMPLITUDES

$\Delta(1700) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.104±0.015 OUR ESTIMATE				
0.090±0.025	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
0.111±0.017	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.089±0.033	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.112±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.130±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.123±0.022	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.121±0.004	LI	93	IPWA	$\gamma N \rightarrow \pi N$
+0.130±0.037	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.072±0.033	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1700) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.085±0.022 OUR ESTIMATE				
0.097±0.020	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
0.107±0.015	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.060±0.015	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.047±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.050±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.102±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.115±0.004	LI	93	IPWA	$\gamma N \rightarrow \pi N$
+0.098±0.036	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.087±0.023	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

Δ(1700) FOOTNOTES

[1] Problems with CHEW 80 are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

Δ(1700) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

Δ(1750) P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Δ(1750) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 1750 OUR ESTIMATE				
1744 ±36	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1715.2±21.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1778.4± 9.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1750) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300 ±120	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.3± 55.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
23.0± 29.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1750) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N(1440)\pi$

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.08±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.20	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1700) \to N(1440)\pi$ $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.15±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

Δ(1750) FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the Δ(1910). Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

Δ(1750) REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT)
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
HOEHLER	83	Landoit-Boernstein 1/9B2		(KARLT)
CHEW	80	Toronto Conf. 123		(LBL)

Δ(1900) S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

Δ(1900) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1850 to 1950 (≈ 1900) OUR ESTIMATE				
1920 ±24	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1890 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1908 ±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1918.5±23.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1803	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

Δ(1900) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
140 to 240 (≈ 200) OUR ESTIMATE				
263 ±39	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
170 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
140 ±40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.5±54.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
137	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

Δ(1900) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1780	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
1870±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
2029 or 2025	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
180±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
164 or 163	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

Δ(1900) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
+20±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1900) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–30 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	
Γ_7	$N\rho$, $S=1/2$, S-wave	
Γ_8	$N\rho$, $S=3/2$, D-wave	
Γ_9	$N(1440)\pi$, S-wave	
Γ_{10}	$N\gamma$, helicity=1/2	

Δ(1900) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1 to 0.3 OUR ESTIMATE				
0.41±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1900) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.03	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.076	[3] DEANS 75	DPWA	$\pi N \to \Sigma K$
0.11	LANGBEIN 73	IPWA	$\pi N \to \Sigma K$ (sol. 1)
0.12	LANGBEIN 73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1900) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$+0.25\pm0.07$	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1900) \to N\rho$, $S=1/2$, S-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.14 ± 0.11	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1900) \to N\rho$, $S=3/2$, D-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.37 ± 0.07	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1900) \to N(1440)\pi$, S-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.16 ± 0.11	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1900)$ PHOTON DECAY AMPLITUDES

$\Delta(1900) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
-0.004 ± 0.016	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.029 ± 0.008	AWAJI 81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.006 to -0.025	CRAWFORD 80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[3] The value given is from solution 1; the resonance is not present in solutions 2, 3, or 4.

$\Delta(1900)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$\Delta(1905)$ F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1905)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1870 to 1920 (≈ 1905) OUR ESTIMATE			
1881 ±18	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1910 ±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1905 ±20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1895 ± 8	ARNDT 96	IPWA	$\gamma N \to \pi N$
1850	ARNDT 95	DPWA	$\pi N \to N\pi$
1960 ±40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1787.0^{+6.0}_{-5.7}$	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1880	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1892	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1830	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1905)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
280 to 440 (≈ 350) OUR ESTIMATE			
327 ± 51	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
400 ±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
260 ± 20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
354 ± 10	ARNDT 96	IPWA	$\gamma N \to \pi N$
294	ARNDT 95	DPWA	$\pi N \to N\pi$
270 ± 40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$66.0^{+24.0}_{-16.0}$	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
193	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
159	BARBOUR 78	DPWA	$\gamma N \to \pi N$
220	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1905)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1800 to 1860 (≈ 1830) OUR ESTIMATE			
1832	ARNDT 95	DPWA	$\pi N \to N\pi$
1829	[2] HOEHLER 93	SPED	$\pi N \to \pi N$
1830±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1794	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
1813 or 1808	[3] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
230 to 330 (≈ 280) OUR ESTIMATE			
254	ARNDT 95	DPWA	$\pi N \to N\pi$
303	[2] HOEHLER 93	SPED	$\pi N \to \pi N$
280±60	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
230	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
193 or 187	[3] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1905)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
12	ARNDT 95	DPWA	$\pi N \to N\pi$
25	HOEHLER 93	SPED	$\pi N \to \pi N$
25±8	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
14	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID	TECN	COMMENT
− 4	ARNDT 95	DPWA	$\pi N \to N\pi$
−50±20	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−40	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1905) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	85–95 %
Γ_4	$\Delta\pi$	<25 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	>60 %
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N\rho$, S=3/2, F-wave	
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\gamma$	0.01–0.03 %
Γ_{12}	$N\gamma$, helicity=1/2	0.0–0.1 %
Γ_{13}	$N\gamma$, helicity=3/2	0.004–0.03 %

Δ(1905) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE			
0.12±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.08±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.15±0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.12	ARNDT 95	DPWA	$\pi N \to N\pi$
0.11	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.015±0.003	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.013	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.021 to 0.054	[4] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.04±0.05	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.02±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.20	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.17	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
+0.06	[6] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.030 to +0.36 OUR ESTIMATE			
+0.33 ±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.33	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.26	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
+0.11 to +0.33	[7] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

Δ(1905) PHOTON DECAY AMPLITUDES

$\Delta(1905) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.026±0.011 OUR ESTIMATE			
0.022±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.021±0.010	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.043±0.020	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.022±0.010	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.031±0.009	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.024±0.014	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.055±0.004	LI 93	IPWA	$\gamma N \to \pi N$
+0.033±0.018	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$\Delta(1905) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.045±0.020 OUR ESTIMATE			
−0.045±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.056±0.028	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.025±0.023	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.029±0.007	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.045±0.006	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.072±0.035	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.002±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.055±0.019	BARBOUR 78	DPWA	$\gamma N \to \pi N$

Δ(1905) FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The range given for DEANS 75 is from the four best solutions.

[5] A Breit-Wigner fit to the HERNDON 75 IPWA.

[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA.

[7] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 90°.

Δ(1905) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1910)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1910) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1870 to 1920 (≈ 1910) OUR ESTIMATE			
1882 ±10	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1910 ±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1888 ±20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2152	ARNDT 95	DPWA	$\pi N \to N\pi$
1960.1±21.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
$2121.4^{+13.0}_{-14.3}$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1921	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1899	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1790	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

Δ(1910) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
190 to 270 (≈ 250) OUR ESTIMATE			
239 ±25	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
225 ±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
280 ±50	HOEHLER 79	IPWA	$\pi N \to \pi N$

• • • We do not use the following data for averages, fits, limits, etc. • • •			
760	ARNDT 95	DPWA	$\pi N \to N\pi$
152.9±60.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
172.2±37.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
351	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
230	BARBOUR 78	DPWA	$\gamma N \to \pi N$
170	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

Δ(1910) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1830 to 1880 (≈ 1855) OUR ESTIMATE			
1810	ARNDT 95	DPWA	$\pi N \to N\pi$
1874	[3] HOEHLER 93	SPED	$\pi N \to \pi N$
1880±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1950	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
1792 or 1801	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
200 to 500 (≈ 350) OUR ESTIMATE			
494	ARNDT 95	DPWA	$\pi N \to N\pi$
283	[3] HOEHLER 93	SPED	$\pi N \to \pi N$
200±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
398	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90
172 or 165	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

Δ(1910) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
53	ARNDT 95	DPWA	$\pi N \to N\pi$
38	HOEHLER 93	SPED	$\pi N \to \pi N$
20±4	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
37	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*	*TECN*	*COMMENT*
−176	ARNDT 95	DPWA	$\pi N \to N\pi$
− 90±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
− 91	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1910) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	15–30 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	
Γ_5	$\Delta(1232)\pi$, *P*-wave	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=3/2, *P*-wave	
Γ_8	$N(1440)\pi$	
Γ_9	$N(1440)\pi$, *P*-wave	
Γ_{10}	$N\gamma$	0.0–0.2 %
Γ_{11}	$N\gamma$, helicity=1/2	0.0–0.2 %

Δ(1910) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.15 to 0.3 OUR ESTIMATE			
0.23±0.08	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.19±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.24±0.06	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.26	ARNDT 95	DPWA	$\pi N \to N\pi$
0.17	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
0.40	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
< 0.03	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.019	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.082 to 0.184	[4] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to \Delta(1232)\pi$, *P*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.06	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to N\rho$, S=3/2, *P*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.29	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.17	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to N(1440)\pi$, *P*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.39±0.04	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

Δ(1910) PHOTON DECAY AMPLITUDES

$\Delta(1910) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.003±0.014 OUR ESTIMATE			
−0.002±0.008	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.014±0.030	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.025±0.011	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.012±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.031±0.004	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.005±0.030	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.032±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.035±0.021	BARBOUR 78	DPWA	$\gamma N \to \pi N$

Δ(1910) FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the $\Delta(1750)$. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] The range given for DEANS 75 is from the four best solutions.

[5] Evidence for this coupling is weak; see NOVOSELLER 78. This coupling assumes the mass is near 1820 MeV.

Δ(1910) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$\Delta(1920)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1920) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1900 to 1970 (≈ 1920) OUR ESTIMATE			
2014 ±16	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1920 ±80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1868 ±10	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1840 ±40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
1955.0±13.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
$2065.0^{+13.6}_{-12.9}$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1920) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
150 to 300 (≈ 200) OUR ESTIMATE			
152 ± 55	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
300 ±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
220 ± 80	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
200 ± 40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
88.3± 35.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
62.0± 44.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1920) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1850 to 1950 (≈ 1900) OUR ESTIMATE			
1900	[2] HOEHLER 93	SPED	$\pi N \to \pi N$
1900±80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
200 to 400 (≈ 300) OUR ESTIMATE			
300±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen	ARNDT 91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1920) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
24±4	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*	*TECN*	*COMMENT*
−150±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(1920) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta(1232)\pi$, P-wave	
Γ_5	$N(1440)\pi$, P-wave	
Γ_6	$N\gamma$, helicity=1/2	
Γ_7	$N\gamma$, helicity=3/2	

Δ(1920) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ $\quad\Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.05 to 0.2 OUR ESTIMATE			
0.02±0.02	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20±0.05	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.14±0.04	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.24	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
0.18	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1920) \to \Sigma K$ $\quad(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.052±0.015	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.049	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.048 to 0.120	[3] DEANS 75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1920) \to \Delta(1232)\pi$, P-wave $\quad(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.13±0.04	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.3	[4] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
0.27	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1920) \to N(1440)\pi$, P-wave $\quad(\Gamma_1\Gamma_5)^{½}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.06±0.07	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

Δ(1920) PHOTON DECAY AMPLITUDES

$\Delta(1920) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.040±0.014	AWAJI 81	DPWA	$\gamma N \to \pi N$

$\Delta(1920) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.023±0.017	AWAJI 81	DPWA	$\gamma N \to \pi N$

Δ(1920) FOOTNOTES

[1] CHEW 80 reports two P_{33} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] The range given for DEANS 75 is from the four best solutions.

[4] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −90°.

[5] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −90°.

Δ(1920) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
NOVOSELLER	78	NP B137 509		(CIT)
NOVOSELLER	78B	NP B137 445		(CIT)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)

$\Delta(1930)\ D_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

Δ(1930) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1920 to 1970 (≈ 1930) OUR ESTIMATE			
1956 ±22	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1940 ±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1901 ±15	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1955 ±15	ARNDT 96	IPWA	$\gamma N \to \pi N$
2056	ARNDT 95	DPWA	$\pi N \to N\pi$
1963	LI 93	IPWA	$\gamma N \to \pi N$
$1910.0^{+15.0}_{-17.2}$	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
2000	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
2024	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
250 to 450 (≈ 350) OUR ESTIMATE				
530 ±140	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
320 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
195 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
350 ± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
590	ARNDT	95	DPWA	$\pi N \to N\pi$
260	LI	93	IPWA	$\gamma N \to \pi N$
$74.8^{+17.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
442	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
462	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1840 to 1940 (≈ 1890) OUR ESTIMATE				
1913	ARNDT	95	DPWA	$\pi N \to N\pi$
1850	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
1890±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2018	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 300 (≈ 250) OUR ESTIMATE				
246	ARNDT	95	DPWA	$\pi N \to N\pi$
180	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
398	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1930)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
8	ARNDT	95	DPWA	$\pi N \to N\pi$
20	HOEHLER	93	SPED	$\pi N \to \pi N$
18±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−47	ARNDT	95	DPWA	$\pi N \to N\pi$
−20±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−24	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1930)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$N\gamma$	0.0–0.02 %
Γ_5	$N\gamma$, helicity=1/2	0.0–0.01 %
Γ_6	$N\gamma$, helicity=3/2	0.0–0.01 %

$\Delta(1930)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ $\qquad\qquad$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1 to 0.2 OUR ESTIMATE				
0.18±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.14±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	ARNDT	95	DPWA	$\pi N \to N\pi$
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1930) \to \Sigma K$ $\qquad\qquad$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.031	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.018 to 0.035	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1930) \to N\pi\pi$ $\qquad\qquad$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1930)$ PHOTON DECAY AMPLITUDES

$\Delta(1930) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.009±0.028 OUR ESTIMATE				
−0.007±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.009±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.030±0.047	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.019±0.001	LI	93	IPWA	$\gamma N \to \pi N$
−0.062±0.064	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.018±0.028 OUR ESTIMATE				
0.005±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.025±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.033±0.060	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.009±0.001	LI	93	IPWA	$\gamma N \to \pi N$
+0.019±0.054	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] The range given for DEANS 75 is from the four best solutions.

$\Delta(1930)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1940)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

$\Delta(1940)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 1940 OUR ESTIMATE				
2057 ±110	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2058.1± 34.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1940 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
460 ±320	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
198.4± 45.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
200 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1900±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1915 or 1926	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 or 186	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1940)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
135±45	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK
Γ_3	$N\pi\pi$
Γ_4	$\Delta(1232)\pi$, S-wave
Γ_5	$\Delta(1232)\pi$, D-wave
Γ_6	$N\rho$, $S=3/2$, S-wave
Γ_7	$N\gamma$, helicity=1/2
Γ_8	$N\gamma$, helicity=3/2

$\Delta(1940)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.12	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1940) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.27±0.16	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1940) \to N\rho$, $S=3/2$, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1940)$ PHOTON DECAY AMPLITUDES

$\Delta(1940) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.036±0.058	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.031±0.012	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$\Delta(1940)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$\Delta(1950)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1950)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1940 to 1960 (≈ 1950) OUR ESTIMATE				
1945 ± 2	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1950 ±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1913 ± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1947 ± 9	ARNDT	96	IPWA	$\gamma N \to \pi N$
1921	ARNDT	95	DPWA	$\pi N \to N\pi$
1940	LI	93	IPWA	$\gamma N \to \pi N$
1925 ±20	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1855.0^{+11.0}_{-10.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1902	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1912	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1925	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
290 to 350 (≈ 300) OUR ESTIMATE				
300 ± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
340 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
224 ±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
302 ± 9	ARNDT	96	IPWA	$\gamma N \to \pi N$
232	ARNDT	95	DPWA	$\pi N \to N\pi$
306	LI	93	IPWA	$\gamma N \to \pi N$
330 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$157.2^{+22.0}_{-19.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
225	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
198	BARBOUR	78	DPWA	$\gamma N \to \pi N$
240	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880 to 1890 (≈ 1885) OUR ESTIMATE				
1880	ARNDT	95	DPWA	$\pi N \to N\pi$
1878	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
1890±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1884	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1924 or 1924	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
210 to 270 (≈ 240) OUR ESTIMATE				
236	ARNDT	95	DPWA	$\pi N \to N\pi$
230	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
260±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
258 or 258	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
54	ARNDT	95	DPWA	$\pi N \to N\pi$
47	HOEHLER	93	ARGD	$\pi N \to \pi N$
50±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
61	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−17	ARNDT	95	DPWA	$\pi N \to N\pi$
−32	HOEHLER	93	ARGD	$\pi N \to \pi N$
−33±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−23	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1950) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–40 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, F-wave	
Γ_6	$\Delta(1232)\pi$, H-wave	
Γ_7	$N\rho$	<10 %
Γ_8	$N\rho$, S=1/2, F-wave	
Γ_9	$N\rho$, S=3/2, F-wave	
Γ_{10}	$N\gamma$	0.08–0.13 %
Γ_{11}	$N\gamma$, helicity=1/2	0.03–0.055 %
Γ_{12}	$N\gamma$, helicity=3/2	0.05–0.075 %

Δ(1950) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.35 to 0.4 OUR ESTIMATE			
0.38±0.01	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.39±0.04	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.38±0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.49	ARNDT 95	DPWA	$\pi N \to N\pi$
0.44	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1950) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.053±0.005	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.022 to 0.040	[4] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1950) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.28 to +0.32 OUR ESTIMATE			
+0.27±0.02	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.32	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.21	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
0.38	[6] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1950) \to N\rho$, S=3/2, F-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.24	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.24	[7] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
0.43	[8] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

Δ(1950) PHOTON DECAY AMPLITUDES

$\Delta(1950) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.076±0.012 OUR ESTIMATE			
−0.079±0.006	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.068±0.007	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.091±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.083±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.067±0.014	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.102±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.058±0.013	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$\Delta(1950) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.097±0.010 OUR ESTIMATE			
−0.103±0.006	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.094±0.016	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.101±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.100±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.082±0.017	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.115±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.075±0.020	BARBOUR 78	DPWA	$\gamma N \to \pi N$

Δ(1950) FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[5] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −60°.

[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −60°.

[7] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near 120°.

[8] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 120°.

Δ(1950) REFERENCES

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(2000)$ F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2000) BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2000 OUR ESTIMATE			
1752± 32	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2200±125	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(2000) BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
251± 93	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
400±125	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(2000) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2150±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
350±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(2000) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
16±5	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID	TECN	COMMENT
150±90	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(2000) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$\Delta(1232)\pi$, P-wave
Γ_4	$\Delta(1232)\pi$, F-wave
Γ_5	$N\rho$, S=3/2, P-wave

$\Delta(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ± 0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.07 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.07\pm0.03$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.09\pm0.04$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2000) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.06 ± 0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(2000)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2150)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2150)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2150 OUR ESTIMATE				
$2047.4\pm\ 27.0$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2203.2\pm\ 8.4$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2150\ \pm100$	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$121.6\pm\ 62.0$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$120.5\pm\ 45.0$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$200\ \pm100$	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2140 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2\times$IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
7 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
-60 ± 90	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2150)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.41	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.37	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.08 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2150) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2150)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

$\Delta(2150)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2200)$ G_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

The various analyses are not in good agreement.

$\Delta(2200)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
2200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2215 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
2280 ± 80	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2280 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2200)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
450 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
400 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
400 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$400\pm\ 50$	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2\times$IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
340 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2200)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
-70 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.05 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2200) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.014 ± 0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2200)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2300)$ H_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^+)$ Status: **

OMITTED FROM SUMMARY TABLE

$\Delta(2300)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2300 OUR ESTIMATE				
2204.5 ± 3.4	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2400 ± 125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2217 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2450 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2300)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
32.3 ± 1.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
425 ± 150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500 ± 200	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2300)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2370 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
420 ± 160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2300)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10 ± 4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−20 ± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2300)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2300)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.06 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.03 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(2300) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.017	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2300)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2350)$ D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2350)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2350 OUR ESTIMATE				
2171 ± 18	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2400 ± 125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2305 ± 26	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(2350)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
264 ± 51	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
400 ± 150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ± 70	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(2350)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2400 ± 125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
400 ± 150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2350)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
15 ± 8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−70 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2350)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2350)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.020 ± 0.003	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20 ± 0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(2350) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2350)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$\Delta(2390)\ F_{37}$

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Δ(2390) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2390 OUR ESTIMATE				
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2425± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2390) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2390) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
260±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2390) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
12±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−90±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2390) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2390) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.08±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2390) \to \Sigma K$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2390) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$\Delta(2400)\ G_{39}$

$I(J^P) = \frac{3}{2}(\frac{9}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

Δ(2400) BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2400 OUR ESTIMATE				
2300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2468± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
330±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
480±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±200	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
320±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
8±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−25±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2400) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.06±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.10±0.03	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2400) \to \Sigma K$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2400) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2420)$ $H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(2420)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2300 to 2500 (≈ 2420) OUR ESTIMATE				
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2416 ± 17	HOEHLER	79	IPWA	$\pi N \to \pi N$
2400 ± 60	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
2358.0± 9.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(2420)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 to 500 (≈ 400) OUR ESTIMATE				
450 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
340 ± 28	HOEHLER	79	IPWA	$\pi N \to \pi N$
460 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
202.2± 45.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(2420)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2260 to 2400 (≈ 2330) OUR ESTIMATE				
2300	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
2360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 to 750 (≈ 550) OUR ESTIMATE				
620	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
420±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2420)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
39	HOEHLER	93	ARGD	$\pi N \to \pi N$
18±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−60	HOEHLER	93	ARGD	$\pi N \to \pi N$
−30±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2420)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	

$\Delta(2420)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.11±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(2420) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.016	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2420)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

$\Delta(2420)$ REFERENCES

HOEHLER	93	πN Newsletter 9 1		(KARL)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2750)$ $I_{3,13}$

$I(J^P) = \frac{3}{2}(\frac{13}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Delta(2750)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2750 OUR ESTIMATE				
2794± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2650±100	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2750)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500±100	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2750)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$\Delta(2750)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.05±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2750)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2950)$ $K_{3,15}$

$I(J^P) = \frac{3}{2}(\frac{15}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Delta(2950)$ BREIT-WIGNER MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2950 OUR ESTIMATE				
2990±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
2850±100	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2950)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
330±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
700±200	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2950)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$\Delta(2950)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.03±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2950)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-3/2 resonances found in partial-wave analyses.

Our 1982 edition also had a $\Delta(2850)$ and a $\Delta(3230)$. The evidence for them was deduced from total cross-section and 180° elastic cross-section measurements. The $\Delta(2850)$ has been resolved into the $\Delta(2750)$ $I_{3,13}$ and $\Delta(2950)$ $K_{3,15}$. The $\Delta(3230)$ is perhaps related to the $K_{3,13}$ of HENDRY 78 and to the $L_{3,17}$ of KOCH 80.

$\Delta(\sim 3000)$ BREIT-WIGNER MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 3000 OUR ESTIMATE				
3300	[1] KOCH	80	IPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3500	[1] KOCH	80	IPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
2850±150	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
3200±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
3300±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3700±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
4100±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
700±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
1000±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
1100±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
1300±400	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
1600±500	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$\Delta(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.06 ±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
0.045±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
0.03 ±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
0.025±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
0.018±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ FOOTNOTES

[1] In addition, KOCH 80 reports some evidence for an S_{31} $\Delta(2700)$ and a P_{33} $\Delta(2800)$.

$\Delta(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Λ BARYONS
$(S = -1,\ I = 0)$

$\Lambda^0 = uds$

Λ

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Λ MASS

The fit uses Λ, Σ^+, Σ^0, Σ^- mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1115.683±0.006 OUR FIT					
1115.683±0.006 OUR AVERAGE					
1115.678±0.006±0.006	20k	HARTOUNI	94	SPEC	pp 27.5 GeV/c
1115.690±0.008±0.006	18k	[1] HARTOUNI	94	SPEC	pp 27.5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1115.59 ±0.08	935	HYMAN	72	HEBC	
1115.39 ±0.12	195	MAYEUR	67	EMUL	
1115.6 ±0.4		LONDON	66	HBC	
1115.65 ±0.07	488	[2] SCHMIDT	65	HBC	
1115.44 ±0.12		[3] BHOWMIK	63	RVUE	

[1] We assume CPT invariance: this is the $\overline{\Lambda}$ mass as measured by HARTOUNI 94. See below for the fractional mass difference, testing CPT.

[2] The SCHMIDT 65 masses have been reevaluated using our April 1973 proton and $K^\pm$ and $\pi^\pm$ masses. P. Schmidt, private communication (1974).

[3] The mass has been raised 35 keV to take into account a 46 keV increase in the proton mass and an 11 keV decrease in the $\pi^\pm$ mass (note added Reviews of Modern Physics **39** 1 (1967)).

$(m_\Lambda - m_{\overline{\Lambda}}) \,/\, m_\Lambda$

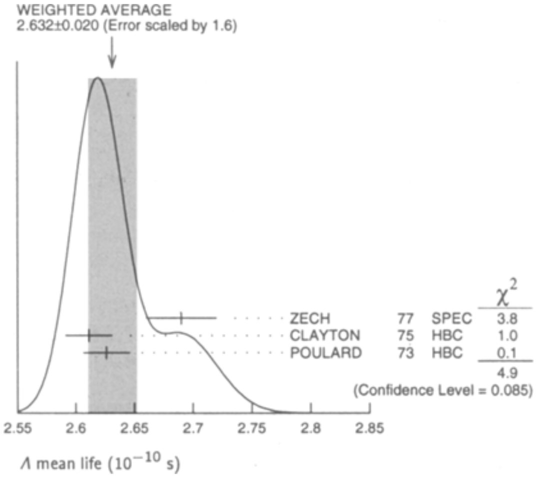
A test of CPT invariance.

VALUE (units 10^{-5})	*DOCUMENT ID*		*TECN*	*COMMENT*
− 1.0 ± 0.9 OUR AVERAGE				
− 1.08± 0.90	HARTOUNI	94	SPEC	pp 27.5 GeV/c
−26 ±13	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$
4.5 ± 5.4	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

Λ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted altogether, and only the latest high-statistics measurements are used for the average.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.632±0.020 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
2.69 ±0.03	53k	ZECH	77	SPEC	Neutral hyperon beam
2.611±0.020	34k	CLAYTON	75	HBC	0.96–1.4 GeV/c K^-p
2.626±0.020	36k	POULARD	73	HBC	0.4–2.3 GeV/c K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.69 ±0.05	6582	ALTHOFF	73B	OSPK	$\pi^+ n \to \Lambda K^+$
2.54 ±0.04	4572	BALTAY	71B	HBC	K^-p at rest
2.535±0.035	8342	GRIMM	68	HBC	
2.47 ±0.08	2600	HEPP	68	HBC	
2.35 ±0.09	916	BURAN	66	HLBC	
$2.452^{+0.056}_{-0.054}$	2213	ENGELMANN	66	HBC	
2.59 ±0.09	794	HUBBARD	64	HBC	
2.59 ±0.07	1378	SCHWARTZ	64	HBC	
2.36 ±0.06	2239	BLOCK	63	HEBC	



$(\tau_\Lambda - \tau_{\overline{\Lambda}}) \,/\, \tau_{\text{average}}$

A test of CPT invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.044±0.085	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$

BARYON MAGNETIC MOMENTS

Written 1994 by C.G. Wohl (LBNL).

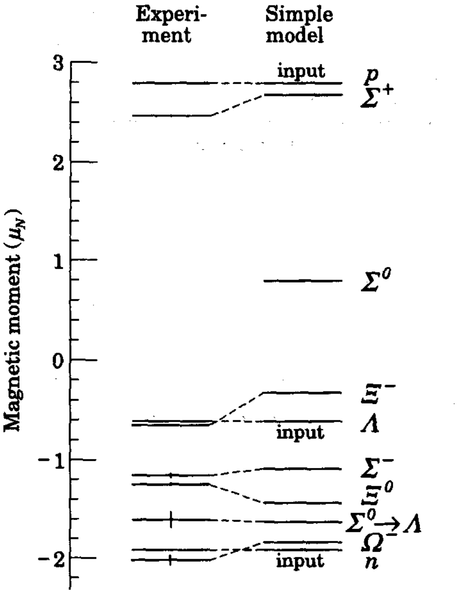
The figure shows the measured magnetic moments of the stable baryons. It also shows the predictions of the simplest quark model, using the measured p, n, and Λ moments as input. In this model, the moments are [1]

$$\begin{aligned}
\mu_p &= (4\mu_u - \mu_d)/3 & \mu_n &= (4\mu_d - \mu_u)/3 \\
\mu_{\Sigma^+} &= (4\mu_u - \mu_s)/3 & \mu_{\Sigma^-} &= (4\mu_d - \mu_s)/3 \\
\mu_{\Xi^0} &= (4\mu_s - \mu_u)/3 & \mu_{\Xi^-} &= (4\mu_s - \mu_d)/3 \\
\mu_\Lambda &= \mu_s & \mu_{\Sigma^0} &= (2\mu_u + 2\mu_d - \mu_s)/3
\end{aligned}$$

$$\mu_{\Omega^-} = 3\mu_s$$

and the $\Sigma^0 \to \Lambda$ transition moment is

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3}\ .$$



The quark moments that result from this model are $\mu_u = +1.852\,\mu_N$, $\mu_d = -0.972\,\mu_N$, and $\mu_s = -0.613\,\mu_N$. The corresponding effective quark masses, taking the quarks to be Dirac point particles, where $\mu = q\hbar/2m$, are 338, 322, and 510 MeV. As the figure shows, the model gives a good first approximation to the experimental moments. For efforts to make a better model, we refer to the literature [2].

References

1. See, for example, D.H. Perkins, *Introduction to High Energy Physics* (Addison-Wesley, Reading, MA, 1987), or D. Griffiths, *Introduction to Elementary Particles* (Harper & Row, New York, 1987).
2. See, for example, J. Franklin, Phys. Rev. **D29**, 2648 (1984); H.J. Lipkin, Nucl. Phys. **B241**, 477 (1984); K. Suzuki, H. Kumagai, and Y. Tanaka, Europhys. Lett. **2**, 109 (1986); S.K. Gupta and S.B. Khadkikar, Phys. Rev. **D36**, 307 (1987); M.I. Krivoruchenko, Sov. J. Nucl. Phys. **45**, 109 (1987); L. Brekke and J.L. Rosner, Comm. Nucl. Part. Phys. **18**, 83 (1988); K.-T. Chao, Phys. Rev. **D41**, 920 (1990) and references cited therein Also, see references cited in discussions of results in the experimental papers..

Λ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" above. Measurements with an error $\geq 0.15\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.613 ±0.004 OUR AVERAGE				
−0.606 ±0.015	200k	COX 81	SPEC	
−0.6138±0.0047	3M	SCHACHIN... 78	SPEC	
−0.59 ±0.07	350k	HELLER 77	SPEC	
−0.57 ±0.05	1.2M	BUNCE 76	SPEC	
−0.66 ±0.07	1300	DAHL-JENSEN 71	EMUL	200 kG field

Λ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-16} *e*cm)	*CL%*	*DOCUMENT ID*	*TECN*
< 1.5	95	[4] PONDROM 81	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<100	95	[5] BARONI 71	EMUL
<500	95	GIBSON 66	EMUL

[4] PONDROM 81 measures $(-3.0 \pm 7.4) \times 10^{-17}$ *e*-cm.

[5] BARONI 71 measures $(-5.9 \pm 2.9) \times 10^{-15}$ *e*-cm.

Λ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^-$	(63.9 ±0.5) %
Γ_2	$n\pi^0$	(35.8 ±0.5) %
Γ_3	$n\gamma$	(1.75±0.15) × 10^{-3}
Γ_4	$p\pi^-\gamma$	[a] (8.4 ±1.4) × 10^{-4}
Γ_5	$pe^-\overline{\nu}_e$	(8.32±0.14) × 10^{-4}
Γ_6	$p\mu^-\overline{\nu}_\mu$	(1.57±0.35) × 10^{-4}

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 20 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 10.5 for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\mathrm{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cccc}
x_2 & -100 & & & \\
x_3 & -2 & -1 & & \\
x_5 & 46 & -46 & -1 & \\
x_6 & 0 & 0 & 0 & 0 \\
\hline
 & x_1 & x_2 & x_3 & x_5
\end{array}$$

Λ BRANCHING RATIOS

$\Gamma(p\pi^-)/\Gamma(N\pi)$ $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.641±0.005 OUR FIT				
0.640±0.005 OUR AVERAGE				
0.646±0.008	4572	BALTAY 71B	HBC	$K^- p$ at rest
0.635±0.007	6736	DOYLE 69	HBC	$\pi^- p \rightarrow \Lambda K^0$
0.643±0.016	903	HUMPHREY 62	HBC	
0.624±0.030		CRAWFORD 59B	HBC	$\pi^- p \rightarrow \Lambda K^0$

$\Gamma(n\pi^0)/\Gamma(N\pi)$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.369±0.005 OUR FIT			
0.310±0.028 OUR AVERAGE			
0.35 ±0.05		BROWN 63	HLBC
0.291±0.034	75	CHRETIEN 63	HLBC

$\Gamma(n\gamma)/\Gamma_{\mathrm{total}}$ Γ_3/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.75±0.15 OUR FIT				
1.75±0.15	1816	LARSON 93	SPEC	$K^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.78\pm0.24^{+0.14}_{-0.16}$	287	NOBLE 92	SPEC	See LARSON 93

$\Gamma(n\gamma)/\Gamma(n\pi^0)$ Γ_3/Γ_2

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.86±0.74±0.57	24	BIAGI 86	SPEC	SPS hyperon beam

$\Gamma(p\pi^-\gamma)/\Gamma(p\pi^-)$ Γ_4/Γ_1

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.32±0.22	72	BAGGETT 72C	HBC	$\pi^- < 95$ MeV/c

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(p\pi^-)$ Γ_5/Γ_1

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.301±0.019 OUR FIT				
1.301±0.019 OUR AVERAGE				
1.335±0.056	7111	BOURQUIN 83	SPEC	SPS hyperon beam
1.313±0.024	10k	WISE 80	SPEC	
1.23 ±0.11	544	LINDQUIST 77	SPEC	$\pi^- p \rightarrow K^0 \Lambda$
1.27 ±0.07	1089	KATZ 73	HBC	
1.31 ±0.06	1078	ALTHOFF 71	OSPK	
1.17 ±0.13	86	[6] CANTER 71	HBC	$K^- p$ at rest
1.20 ±0.12	143	[7] MALONEY 69	HBC	
1.17 ±0.18	120	[7] BAGLIN 64	FBC	K^- freon 1.45 GeV/c
1.23 ±0.20	150	[7] ELY 63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.32 ±0.15	218	[6] LINDQUIST 71	OSPK	See LINDQUIST 77

[6] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ assuming the authors used $\Gamma(p\pi^-)/\Gamma_{\mathrm{total}} = 2/3$.

[7] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ because $\Gamma(pe^-\nu)/\Gamma(p\pi^-)$ is the directly measured quantity.

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(N\pi)$ $\Gamma_6/(\Gamma_1+\Gamma_2)$

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.57±0.35 OUR FIT				
1.57±0.35 OUR AVERAGE				
1.4 ±0.5	14	BAGGETT 72B	HBC	$K^- p$ at rest
2.4 ±0.8	9	CANTER 71B	HBC	$K^- p$ at rest
1.3 ±0.7	3	LIND 64	RVUE	
1.5 ±1.2	2	RONNE 64	FBC	

Λ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. Some early results have been omitted.

α_- FOR $\Lambda \to p\pi^-$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.642±0.013 OUR AVERAGE					
0.584±0.046	8500	ASTBURY	75	SPEC	
0.649±0.023	10325	CLELAND	72	OSPK	
0.67 ±0.06	3520	DAUBER	69	HBC	From Ξ decay
0.645±0.017	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	63	CNTR	Λ from $\pi^- p$

ϕ ANGLE FOR $\Lambda \to p\pi^-$ $(\tan\phi = \beta / \gamma)$

VALUE (°)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
− 6.5± 3.5 OUR AVERAGE					
− 7.0± 4.5	10325	CLELAND	72	OSPK	Λ from $\pi^- p$
− 8.0± 6.0	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
13.0±17.0	1156	CRONIN	63	OSPK	Λ from $\pi^- p$

$\alpha_0 / \alpha_- = \alpha(\Lambda \to n\pi^0) / \alpha(\Lambda \to p\pi^-)$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.01 ±0.07 OUR AVERAGE					
1.000±0.068	4760	[8] OLSEN	70	OSPK	$\pi^+ n \to \Lambda K^+$
1.10 ±0.27		CORK	60	CNTR	

[8] OLSEN 70 compares proton and neutron distributions from Λ decay.

$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})] / [\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$

Zero if *CP* is conserved.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.03±0.06 OUR AVERAGE					
+0.01±0.10	770	TIXIER	88	DM2	$J/\psi \to \Lambda\overline{\Lambda}$
−0.07±0.09	4063	BARNES	87	CNTR	$\overline{p}p \to \overline{\Lambda}\Lambda$ LEAR
−0.02±0.14	10k	[9] CHAUVAT	85	CNTR	pp, $\overline{p}p$ ISR

[9] CHAUVAT 85 actually gives $\alpha_+(\overline{\Lambda})/\alpha_-(\Lambda) = -1.04 \pm 0.29$. Assumes polarization is same in $\overline{p}p \to \overline{\Lambda}X$ and $pp \to \Lambda X$. Tests of this assumption, based on *C*-invariance and fragmentation, are satisfied by the data.

g_A / g_V FOR $\Lambda \to pe^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the "Note on Baryon Decay Parameters" in the neutron Listings. The measurements all assume that the form factor $g_2 = 0$. See also the footnote on DWORKIN 90.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.718±0.015 OUR AVERAGE					
−0.719±0.016±0.012	37k	[10] DWORKIN	90	SPEC	$e\nu$ angular corr.
−0.70 ±0.03	7111	BOURQUIN	83	SPEC	$\Xi \to \Lambda\pi^-$
−0.734±0.031	10k	[11] WISE	81	SPEC	$e\nu$ angular correl.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.63 ±0.06	817	ALTHOFF	73	OSPK	Polarized Λ

[10] The tabulated result assumes the weak-magnetism coupling $w \equiv g_W(0)/g_V(0)$ to be 0.97, as given by the CVC hypothesis and as assumed by the other listed measurements. However, DWORKIN 90 *measures* w to be 0.15 ± 0.30, and then $g_A/g_V = -0.731 \pm 0.016$.

[11] This experiment measures only the absolute value of g_A/g_V.

Λ REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

HARTOUNI	94	PRL 72 1322	+Jensen, Kreisler+	(BNL E766 Collab.)
Also	94B	PRL 72 2821 (erratum)	Hartouni, Jensen+	(BNL E766 Collab.)
LARSON	93	PR D47 799	+Noble, Bassalleck+	(BNL-811 Collab.)
NOBLE	92	PRL 69 414	+	(BIRM, BOST, BRCO, BNL, CASE, BUDA, LANL+)
DWORKIN	90	PR D41 780	+Cox, Dukes, Overseth+	(MICH, WISC, RUTG, MINN)
TIXIER	88	PL B212 523	+Ajaltouni, Falvard, Jousset+	(DM2 Collab.)
BARNES	87	PL B199 147	+	(CMU, SACL, LANL, VIEN, FREIB, ILL, UPPS+)
BIAGI	86	ZPHY C30 201	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
CHAUVAT	85	PL 163B 273	+Erhan, Hayes+	(CERN, CLER, UCLA, SACL)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
PONDROM	81	PR D23 814	+Handler, Sheaff, Cox+	(WISC, MICH, RUTG, MINN)
WISE	81	PL 98B 123	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
WISE	80	PL 91B 165	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
SCHACHIN...	78	PRL 41 1348	Schachinger, Bunce, Cox+	(MICH, RUTG, WISC)
HELLER	77	PL 68B 480	+Overseth, Bunce, Dydak+	(MICH, WISC, HEIDH)
LINDQUIST	77	PR D16 2104	+Swallow, Sumner+	(EFI, OSU, ANL)
Also	76	JPG 2 L211	Lindquist, Swallow+	(EFI, WUSL, OSU, ANL)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEIDH)
BUNCE	76	PRL 36 1113	+Handler, March, Martin+	(WISC, MICH, RUTG)
ASTBURY	75	NP B99 30	+Gallivan, Jafar+	(LOIC, CERN, ETH, SACL)
CLAYTON	75	NP B95 130	+Bacon, Butterworth, Waters+	(LOIC, RHEL)
ALTHOFF	73	PL 43B 237	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
ALTHOFF	73B	NP B66 29	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
KATZ	73	Thesis MDDP-TR-74-044		(UMD)
POULARD	73	PL 46B 135	+Givernaud, Borg	(SACL)
BAGGETT	72B	ZPHY 252 362	+Baggett, Eisele, Filthuth, Frehse+	(HEID)
BAGGETT	72C	PL 42B 379	+Baggett, Eisele, Filthuth, Frehse, Hepp+	(HEID)
CLELAND	72	NP B40 221	+Conforto, Eaton, Gerber+	(CERN, GEVA, LUND)
HYMAN	72	PR D5 1063	+Bunnell, Derrick, Fields, Katz+	(ANL, CMU)
ALTHOFF	71	PL 37B 531	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
BALTAY	71B	PR D4 670	+Bridgewater, Cooper, Habibi+	(COLU, BING)
BARONI	71	LNC 2 1256	+Petrera, Romano	(ROMA)
CANTER	71	PRL 26 868	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
CANTER	71B	PRL 27 59	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
DAHL-JENSEN	71	NC 3A 1	+	(CERN, ANKA, LAUS, MPIM, ROMA)
LINDQUIST	71	PRL 27 612	+Sumner+	(EFI, WUSL, OSU, ANL)
OLSEN	70	PRL 24 843	+Pondrom, Handler, Limon, Smith+	(WISC, MICH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
DOYLE	69	Thesis UCRL 18139		(LRL)
MALONEY	69	PRL 23 425	+Sechi-Zorn	(UMD)
GRIMM	68	NC 54A 187		(HEID)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
BADIER	67	PL 25B 152	+Bonnet, Briandet, Sadoulet	(EPOL)
MAYEUR	67	U.Libr.Brux.Bul. 32	+Tompa, Wickens	(BELG, LOUC)
OVERSETH	67	PRL 19 391	+Roth	(MICH, PRIN)
PDG	67	RMP 39 1	Rosenfeld, Barbaro-Galtieri, Podolsky+	(LRL, CERN, YALE)
BURAN	66	PL 20 318	+Eivindson, Skjeggestad, Tofte+	(OSLO)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
ENGELMANN	66	NC 45A 1038	+Filthuth, Alexander+	(HEID, REHO)
GIBSON	66	NC 45A 882	+Green	(BRIS)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
SCHMIDT	65	PR 140B 1328		(COLU)
BAGLIN	64	NC 35 977	+Bingham+	(EPOL, CERN, LOUC, RHEL, BERG)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
LIND	64	PR 135B 1483	+Binford, Good, Stern	(WISC)
RONNE	64	PL 11 357	+	(CERN, EPOL, LOUC, BERG+)
SCHWARTZ	64	Thesis UCRL 11360		(LRL)
BHOWMIK	63	NC 28 1494	+Goyal	(DELH)
BLOCK	63	PR 130 766	+Gessaroli, Ratti+	(NWES, BGNA, SYRA, ORNL)
BROWN	63	PR 130 769	+Kadyk, Trilling, Roe+	(LRL, MICH)
CHRETIEN	63	PR 131 2208	+	(BRAN, BROW, HARV, MIT)
CRONIN	63	PR 129 1795	+Overseth	(PRIN)
ELY	63	PR 131 868	+Gidal, Kalmus, Oswald, Powell+	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)
CORK	60	PR 120 1000	+Kerth, Wenzel, Cronin+	(LRL, PRIN, BNL)
CRAWFORD	59B	PRL 2 266	+Cresti, Douglass, Good, Ticho+	(LRL)

Λ AND Σ RESONANCES

Introduction: There are no new results at all on Λ and Σ resonances. The field remains at a standstill and will only be revived if a kaon factory is built. What follows is a much abbreviated version of the note on Λ and Σ Resonances from our 1990 edition. In particular, see that edition for some representative Argand plots from partial-wave analyses.

Table 1 is an attempt to evaluate the status, both overall and channel by channel, of each Λ and Σ resonance in the Particle Listings. The evaluations are of course partly subjective. A blank indicates there is no evidence at all: either the relevant couplings are small or the resonance does not really exist. The main Baryon Summary Table includes only the established resonances (overall status 3 or 4 stars). A number of the 1- and 2-star entries may eventually disappear, but there are certainly many resonances yet to be discovered underlying the established ones.

Sign conventions for resonance couplings: In terms of the isospin-0 and -1 elastic scattering amplitudes A_0 and A_1, the amplitude for $K^- p \to \overline{K}^0 n$ scattering is $\pm(A_1 - A_0)/2$, where the sign depends on conventions used in conjunction with the Clebsch-Gordan coefficients (such as, is the baryon or the meson the "first" particle). If this reaction is partial-wave analyzed and if the overall phase is chosen so that, say, the $\Sigma(1775)D_{15}$ amplitude at resonance points along the positive imaginary axis (points "up"), then any Σ at resonance will point "up" and any Λ at resonance will point "down" (along the negative imaginary axis). Thus the phase at resonance determines the isospin. The above ignores background amplitudes in the resonating partial waves.

That is the basic idea. In a similar but somewhat more complicated way, the phases of the $\overline{K}N \to \Lambda\pi$ and $\overline{K}N \to \Sigma\pi$ amplitudes for a resonating wave help determine the SU(3) multiplet to which the resonance belongs. Again, a convention has to be adopted for some overall arbitrary phases: which way is "up"? Our convention is that of Levi-Setti [1] and is shown in Fig. 1, which also compares experimental results with theoretical predictions for the signs of several resonances. In the Listings, a + or − sign in front of a measurement of an inelastic resonance coupling indicates the sign (the *absence* of a sign means that the sign is not determined, *not* that it is positive). For more details, see Appendix II of our 1982 edition [2].

Table 1. The status of the Λ and Σ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —			
Particle	$L_{I\cdot 2J}$	Overall status	$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	P_{01}	****		F		$N\pi$(weakly)
$\Lambda(1405)$	S_{01}	****	****	o	****	
$\Lambda(1520)$	D_{03}	****	****	r	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	P_{01}	***	***	b	**	
$\Lambda(1670)$	S_{01}	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	D_{03}	****	****	d	****	$\Lambda\pi\pi, \Sigma\pi\pi$
$\Lambda(1800)$	S_{01}	***	***	d	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(1810)$	P_{01}	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	F_{05}	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	D_{05}	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	P_{03}	****	****	o	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2020)$	F_{07}	*	*	b	*	
$\Lambda(2100)$	G_{07}	****	****	i	***	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2110)$	F_{05}	***	**	d	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2325)$	D_{03}	*	*	d		$\Lambda\omega$
$\Lambda(2350)$		***	***	e	*	
$\Lambda(2585)$		**	**	n		
$\Sigma(1193)$	P_{11}	****				$N\pi$(weakly)
$\Sigma(1385)$	P_{13}	****		****	****	
$\Sigma(1480)$		*	*	*	*	
$\Sigma(1560)$		**		**	**	
$\Sigma(1580)$	D_{13}	**	*	*		
$\Sigma(1620)$	S_{11}	**	**	*	*	
$\Sigma(1660)$	P_{11}	***	***	*	**	
$\Sigma(1670)$	D_{13}	****	****	****	****	several others
$\Sigma(1690)$		**	*	**	*	$\Lambda\pi\pi$
$\Sigma(1750)$	S_{11}	***	***	**	*	$\Sigma\eta$
$\Sigma(1770)$	P_{11}	*				
$\Sigma(1775)$	D_{15}	****	****	****	***	several others
$\Sigma(1840)$	P_{13}	*	*	**	*	
$\Sigma(1880)$	P_{11}	**	**	**		$N\overline{K}^*$
$\Sigma(1915)$	F_{15}	****	***	****	***	$\Sigma(1385)\pi$
$\Sigma(1940)$	D_{13}	***	*	***	**	quasi-2-body
$\Sigma(2000)$	S_{11}	*		*		$N\overline{K}^*, \Lambda(1520)\pi$
$\Sigma(2030)$	F_{17}	****	****	****	**	several others
$\Sigma(2070)$	F_{15}	*	*		*	
$\Sigma(2080)$	P_{13}	**		**		
$\Sigma(2100)$	G_{17}	*		*	*	
$\Sigma(2250)$		***	***	*	*	
$\Sigma(2455)$		**	*			
$\Sigma(2620)$		**	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				multi-body

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

Errors on masses and widths: The errors quoted on resonance parameters from partial-wave analyses are often only statistical, and the parameters can change by more than these errors when a different parametrization of the waves is used.

Furthermore, the different analyses use more or less the same data, so it is not really appropriate to treat the different determinations of the resonance parameters as independent or to average them together. In any case, the spread of the masses, widths, and branching fractions from the different analyses is certainly a better indication of the uncertainties than are the quoted errors. In the Baryon Summary Table, we usually give a range reflecting the spread of the values rather than a particular value with error.

For three states, the $\Lambda(1520)$, the $\Lambda(1820)$, and the $\Sigma(1775)$, there is enough information to make an overall fit to the various branching fractions. It is then necessary to use the quoted errors, but the errors obtained from the fit should not be taken seriously.

Production experiments: Partial-wave analyses of course separate partial waves, whereas a peak in a cross section or an invariant mass distribution usually cannot be disentangled from background and analyzed for its quantum numbers; and more than one resonance may be contributing to the peak. Results from partial-wave analyses and from production experiments are generally kept separate in the Listings, and in the Baryon Summary Table results from production experiments are used only for the low-mass states. The $\Sigma(1385)$ and $\Lambda(1405)$ of course lie below the $\overline{K}N$ threshold and nearly everything about them is learned from production experiments; and production and formation experiments agree quite well in the case of $\Lambda(1520)$ and results have been combined. There is some disagreement between production and formation experiments in the 1600–1700 MeV region: see the note on the $\Sigma(1670)$.

References

1. R. Levi-Setti, in *Proceedings of the Lund International Conference on Elementary Particles* (Lund, 1969), p. 339.
2. Particle Data Group, Phys. Lett. **111B** (1982).

$\boxed{\Lambda(1405)\ S_{01}}$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

NOTE ON THE $\Lambda(1405)$

Revised March 1998 by R.H. Dalitz (Oxford University).

It is generally accepted that the $\Lambda(1405)$ is a well-established $J^P = 1/2^-$ resonance. It is assigned to the lowest $L = 1$ supermultiplet of the 3-quark system and paired with the $J^P = 3/2^-$ $\Lambda(1520)$. Lying about 30 MeV below the $N\overline{K}$ threshold, the $\Lambda(1405)$ can be observed directly only as a resonance bump in the $(\Sigma\pi)^0$ subsystem in final states of production experiments. It was first reported by ALSTON 61B in the reaction $K^-p \to \Sigma\pi\pi\pi$ at 1.15 GeV/c and has since been seen in at least eight other experiments. However, only two of them had enough events for a detailed analysis: THOMAS 73, with about 400 $\Sigma^\pm\pi^\mp$ events from $\pi^-p \to K^0(\Sigma\pi)^0$ at 1.69 GeV/c; and HEMINGWAY 85, with 766 $\Sigma^+\pi^-$ and 1106 $\Sigma^-\pi^+$ events from $K^-p \to (\Sigma\pi\pi)^+\pi^-$ at 4.2 GeV/c, after the selections $1600 \le M(\Sigma\pi\pi)^+ \le 1720$ MeV and momentum transfer ≤ 1.0 (GeV/c)^2 to purify the $\Lambda(1405) \to (\Sigma\pi)^0$ sample. These experiments agree on a mass of about 1395–1400 MeV and a width of about 60 MeV. (Hemingway's mass of 1391 ± 1 MeV is from his best, but unacceptably poor, Breit-Wigner fit.)

The Byers-Fenster tests on these data allow any spin and either parity: neither J nor P has yet been determined *directly.* The early indications for $J^P = 1/2^-$ came from finding $\mathrm{Re}\,A_{I=0}$ to be large and negative in a constant-scattering-length analysis of low-energy $N\overline{K}$ reaction data (see KIM 65, SAKITT 65, and earlier references cited therein). The first multichannel energy-dependent K-matrix analysis (KIM 67) strengthened the case for a resonance around 1400–1420 MeV strongly coupled to the $I = 0$ S-wave $N\overline{K}$ system.

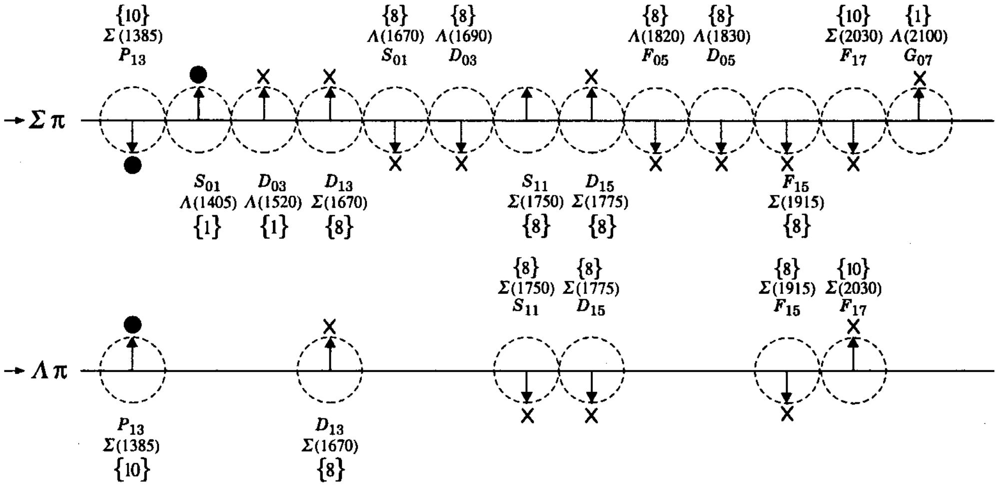


Figure 1. The signs of the imaginary parts of resonating amplitudes in the $\overline{K}N \to \Lambda\pi$ and $\Sigma\pi$ channels. The signs of the $\Sigma(1385)$ and $\Lambda(1405)$, marked with a •, are set by convention, and then the others are determined relative to them. The signs required by the SU(3) assignments of the resonances are shown with an arrow, and the experimentally determined signs are shown with an ×.

THOMAS 73 and HEMINGWAY 85 both found the $\Lambda(1405)$ bump to be asymmetric and not well fitted by a Breit-Wigner resonance function with constant parameters. The asymmetry involves a rapid fall in intensity as the $N\overline{K}$ threshold energy is approached from below. This is readily understood as due to a strong coupling of the $\Lambda(1405)$ to the S-wave $N\overline{K}$ channel (see DALITZ 81). This striking S-shaped cusp behavior at a new threshold is characteristic of S-wave coupling; the other below-threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N\overline{K}$ coupling is P-wave. For the $\Lambda(1405)$, this asymmetry is the *sole direct evidence* that $J^P = 1/2^-$.

Following the early work cited above, a considerable literature has developed on proper procedures for phenomenological extrapolation below the $N\overline{K}$ threshold, partly in order to strengthen the evidence for the spin-parity of the $\Lambda(1405)$, and partly to provide an estimate for the amplitude $f(N\overline{K})$ in the unphysical domain below the $N\overline{K}$ threshold; the latter is needed for the evaluation of the dispersion relation for $N\overline{K}$ and NK forward scattering amplitudes. For recent reviews, see MILLER 84 and BARRETT 89. In most recent work, the $(\Sigma\pi)^0$ production spectrum is included in the data fitted (see, *e.g.*, CHAO 73, MARTIN 81).

It is now accepted that the data can be fitted only with an S-wave pole in the reaction amplitudes below $N\overline{K}$ threshold (see, however, FINK 90), but there is still controversy about the physical origin of this pole (for a review, see DALITZ 81 and DALITZ 82). Two extreme possibilities are: (a) an $L = 1$ SU(3)-singlet *uds* state coupled with the S-wave meson-baryon systems; or (b) an unstable $N\overline{K}$ bound state, analogous to the (stable) deuteron in the NN system. The problem with (a) is that the $\Lambda(1405)$ mass is so much lower than that of its partner, the $\Lambda(1520)$. This requires, in the QCD-inspired quark model, rather large spin-orbit couplings, whether or not one uses relativistic kinetic energies. CAPSTICK 86 and CAPSTICK 89 conclude that a proper QCD calculation leads only to small energy splittings, whereas LEINWEBER 90, using QCD sum rules, obtains a good fit to this splitting.

On the other hand, the problem with (b) is that then another $J^P = 1/2^- \Lambda$ is needed to replace the $\Lambda(1405)$ in the $L = 1$ supermultiplet, and it would have to lie close to the $\Lambda(1520)$, a region already well explored by $N\overline{K}$ experiments without result. Intermediate structures are possible; for example, the cloudy bag model allows the configurations (a) and (b) to mix and finds the intensity of (a) in the $\Lambda(1405)$ to be only 14% (VEIT 84, VEIT 85, JENNINGS 86). Such models naturally predict a second $1/2^-$ Λ close to the $\Lambda(1520)$.

The determination of the mass and width of the resonance from $(\Sigma\pi)^0$ data is usually based on the "Watson approximation," which states that the production rate $R(\Sigma\pi)$ of the $(\Sigma\pi)^0$ state has a mass dependence proportional to $(\sin^2\delta_{\Sigma\pi})/q$, q being the $\Sigma\pi$ c.m. momentum, in a $\Sigma\pi$ mass range where $\delta_{\Sigma\pi}$ is not far from $\pi/2$ and only the $\Sigma\pi$ channel is open, *i.e.*, between the $\Sigma\pi$ and the $N\overline{K}$ thresholds. Then $q\,R(\Sigma\pi)$ is proportional to $\sin^2\delta_{\Sigma\pi}$, and the mass M may be defined as the energy at which $\sin^2\delta_{\Sigma\pi} = 1$. The width Γ may be determined from the rate at which $\delta_{\Sigma\pi}$ goes through $\pi/2$, or from the FWHM; this is a matter of convention.

This determination of M and Γ from the data suffers from the following defects:

(i) The determination of $\sin^2\delta_{\Sigma\pi}$ requires that $R(\Sigma\pi)$ be scaled to give $\sin^2\delta_{\Sigma\pi} = 1$ at the peak for the best fit to the data; *i.e.*, the bump must be *assumed* to arise from a resonance. However, this assumption is supported by the analysis of the low-energy $N\overline{K}$ data and its extrapolation below threshold.

(ii) Owing to the nearby $N\overline{K}$ threshold, the shape of the best fit to the $M(\Sigma\pi)$ bump is uncertain. For energies below this threshold at $E_{N\overline{K}}$, the general form for $\delta_{\Sigma\pi}$ is

$$q\cot\delta_{\Sigma\pi} = \frac{1+\kappa\alpha}{\gamma+\kappa(\alpha\gamma-\beta^2)}\ . \qquad (1)$$

Here α, β, and γ are the (generally energy-dependent) NN, $N\Sigma$, and $\Sigma\Sigma$ elements of the $I = 0$ S-wave K-matrix for the $(\Sigma\pi, N\overline{K})$ system, and κ is the magnitude of the (imaginary) c.m. momentum k_K for the $N\overline{K}$ system below threshold. The elements α, β, γ are real functions of E; they have no branch cuts at the $\Sigma\pi$ and $N\overline{K}$ thresholds, but they are permitted to have poles in E along the real E axis. The resonance asymmetry arises from the effect of κ on $\delta_{\Sigma\pi}$. We note that $\delta_{\Sigma\pi} = \pi/2$ when $\kappa = -1/\alpha$.

Accepting this close connection of $\delta_{\Sigma\pi}$ with the low-energy $N\overline{K}$ data, it is natural to analyze the two sets of data together (*e.g.*, MARTIN 81), and there is now a large body of accurate $N\overline{K}$ data for laboratory momenta between 100 and 300 MeV/c (see MILLER 84). The two sets of data span c.m. energies from 1370 MeV to 1490 MeV, and the K-matrix elements will not be energy independent over such a broad range. For the $I = 0$ channels, a linear energy dependence for K^{-1} has been adopted routinely ever since the work of KIM 67, and it is essential when fitting the $q\,R(\Sigma\pi)$ and $N\overline{K}$ data together. However, $q\,R(\Sigma\pi)$ is not always well fitted in this procedure; the value obtained for the $\Lambda(1405)$ mass M varies a good deal with the type of fit, not a surprising result when the $\Sigma\pi$ mass spectrum below the pK^- threshold contributes only nine data points in a total of about 200. The value of M obtained from an overall fit is not necessarily much better than from one using only the $q\,R(\Sigma\pi)$ data; and M may be a function of the representation—K-matrix, K^{-1}-matrix, relativistic-separable or nonseparable potentials, *etc.*— used in fitting over the full energy range. DALITZ 91 fitted the $q\,R(\Sigma^+\pi^-)$ Hemingway data with each of the first three representations just mentioned, constrained to the $I = 0$ $N\overline{K}$ threshold scattering length from low-energy $N\overline{K}$ data. The (nonseparable) meson-exchange potentials of MÜLLER-GROELING 90, fitted to the low-energy $N\overline{K}$ (and NK) data, predicted an unstable $N\overline{K}$ bound state with mass and width compatible with the $\Lambda(1405)$.

From the measurement of $2p \rightarrow 1s$ x rays from kaonic-hydrogen, the energy-level shift ΔE and width Γ of its 1s state can give us two further constraints on the $(\Sigma\pi, N\overline{K})$

system, at an energy roughly midway between those from the low-energy hydrogen bubble chamber studies and those from $q\,R(\Sigma\pi)$ observations below the pK^- threshold. IWASAKI 97 have reported the first convincing observation of this x ray, with a good initial estimate:

$$\Delta E - i\Gamma/2 = (-323 \pm 63 \pm 11) - i(204 \pm 104 \pm 50)\ \text{eV}\ . \quad (2)$$

The errors here encompass about half of the predictions made following the various analyses and/or models for the in-flight K^-p and sub-threshold $q\,R(\Sigma\pi)$ data. Better measurements will be needed to discriminate between the analyses and predictions. Now that ΔE is known with some certainty, we can anticipate much-improved data on kaonic-hydrogen, perhaps from the DAΦNE storage ring at Frascati, information vital for our quantitative understanding of the $(\Sigma\pi, N\overline{K})$ system in this region. This will lead to better knowledge of kaonic coupling strengths and to more reliable dispersion-theoretic arguments concerning strange-particle processes.

The present status of the $\Lambda(1405)$ thus depends heavily on theoretical arguments, a somewhat unsatisfactory basis for a four-star rating. Nevertheless, there is no known reason to doubt its existence or quantum numbers. The 3-quark model for baryons has been broadly successful in accounting for all of the $L^P = 1^-$ excited baryonic states (CAPSTICK 89), apart from the relatively large mass separation between the $\Lambda(1405)$ and $\Lambda(1520)$. Quark model builders have no reservations about accepting the $\Lambda(1405)$ as a 3-quark state. However, calculations with broken-chiral-symmetric models, which combine internal 3-quark configurations with external meson-baryon states (*e.g.*, VEIT 85, KAISER 95) end up with descriptions of the $\Lambda(1405)$ dominated by the meson-baryon terms in the wavefunctions. Models using meson-baryon potentials readily fit its mass, and give ΔE negative, as is found empirically. The problem is not so much one of "either (a) or (b)," but rather how to achieve "both (a) and (b)." Theoreticians have not yet been able to deal with the full coupled-channels system, with qqq and $qqqq\overline{q}$ configurations (at the least) being treated on the same footing. On the experimental side, better statistics are needed, both above and below the pK^- threshold. To disentangle the physics, the $I = 1$ channels also need more attention. For example, low-energy pK^0_L interactions have not been studied at all in the last 25 years.

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1406.5 ± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
~ 1405	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
1405	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
1400 ± 5	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1382 ± 8		ENGLER	65	HDBC	$\pi^- p$, $\pi^+ d$ 1.68 GeV/c
1400 ±24		MUSGRAVE	65	HBC	$\overline{p}p$ 3–4 GeV/c
1410		ALEXANDER	62	HBC	$\pi^- p$ 2.1 GeV/c
1405		ALSTON	62	HBC	$K^- p$ 1.2–0.5 GeV/c
1405		ALSTON	61B	HBC	$K^- p$ 1.15 GeV/c

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1411	[3] MARTIN	81		K-matrix fit
1406	[4] CHAO	73	DPWA	0–range fit (sol. B)
1421	MARTIN	70	RVUE	Constant K-matrix
1416 ±4	MARTIN	69	HBC	Constant K-matrix
1403 ±3	KIM	67	HBC	K-matrix fit
1407.5±1.2	[5] KITTEL	66	HBC	0–effective-range fit
1410.7±1.0	KIM	65	HBC	0–effective-range fit
1409.6±1.7	[5] SAKITT	65	HBC	0–effective-range fit

Λ(1405) WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
50 ± 2		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
32 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
45 to 55	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
35	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
50 ±10	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
89 ±20		ENGLER	65	HDBC	
60 ±20		MUSGRAVE	65	HBC	
35 ± 5		ALEXANDER	62	HBC	
50		ALSTON	62	HBC	
20		ALSTON	61B	HBC	

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30	[3] MARTIN	81		K-matrix fit
55	[4,6] CHAO	73	DPWA	0–range fit (sol. B)
20	MARTIN	70	RVUE	Constant K-matrix
29 ±6	MARTIN	69	HBC	Constant K-matrix
50 ±5	KIM	67	HBC	K-matrix fit
34.1±4.1	[5] KITTEL	66	HBC	
37.0±3.2	KIM	65	HBC	
28.2±4.1	[5] SAKITT	65	HBC	

Λ(1405) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma\pi$	100 %
Γ_2	$\Lambda\gamma$	
Γ_3	$\Sigma^0\gamma$	
Γ_4	$N\overline{K}$	

Λ(1405) PARTIAL WIDTHS

$\Gamma(\Lambda\gamma)$ Γ_2

VALUE (keV)	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
27±8	BURKHARDT	91	Isobar model fit

$\Gamma(\Sigma^0\gamma)$ Γ_3

VALUE (keV)	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10 ± 4 or 23 ± 7	BURKHARDT	91	Isobar model fit

Λ(1405) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ Γ_4/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3	95	HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c

Λ(1405) FOOTNOTES

[1] DALITZ 91 fits the HEMINGWAY 85 data.
[2] THOMAS 73 data is fit by CHAO 73 (see next section).
[3] The MARTIN 81 fit includes the $K^{\pm} p$ forward scattering amplitudes and the dispersion relations they must satisfy.
[4] See also the accompanying paper of THOMAS 73.
[5] Data of SAKITT 65 are used in the fit by KITTEL 66.
[6] An asymmetric shape, with $\Gamma/2$ = 41 MeV below resonance, 14 MeV above.

$\Lambda(1405)$ REFERENCES

BURKHARDT	91	PR C44 607	+Lowe	(NOTT, UNM, BIRM)	
DALITZ	91	JPG 17 289	+Deloff	(OXFTP, WINR)	
HEMINGWAY	85	NP B253 742		(CERN)	J
MARTIN	81	NP B179 33		(DURH)	
CHAO	73	NP B56 46	+Kraemer, Thomas, Martin	(RHEL, CMU, LOUC)	
THOMAS	73	NP B56 15	+Engler, Fisk, Kraemer	(CMU)	J
MARTIN	70	NP B16 479	+Ross	(DURH)	
MARTIN	69	PR 183 1352	+Sakitt	(LOUC, BNL)	
Also	69B	PR 183 1345	Martin, Sakitt	(LOUC, BNL)	
BARBARO-...	68B	PRL 21 573	Barbaro-Galtieri, Chadwick+	(LRL, SLAC)	
KIM	67	PRL 19 1074		(YALE)	
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)	
KITTEL	66	PL 21 349	+Otter, Wacek	(VIEN)	
ENGLER	65	PRL 15 224	+Fisk, Kraemer, Meltzer, Westgard+	(CMU, BNL)	IJ
KIM	65	PRL 14 29		(COLU)	
MUSGRAVE	65	NC 35 735	+Petmezas+	(BIRM, CERN, EPOL, LOIC, SACL)	
SAKITT	65	PR 139B 719	+Day, Glasser, Seeman, Friedman+	(UMD, LRL)	
ALEXANDER	62	PRL 8 447	+Kalbfleisch, Miller, Smith	(LRL)	I
ALSTON	62	CERN Conf. 311	+Alvarez, Ferro-Luzzi+	(LRL)	I
ALSTON	61B	PRL 6 698	+Alvarez, Eberhard, Good+	(LRL)	I

OTHER RELATED PAPERS

IWASAKI	97	PRL 78 3067	+Hayano, Ito, Nakamura+	(KEK-228 Collab.)
FINK	90	PR C41 2720	+He, Landau, Schnick	(IBMY, ORST, ANSM)
LEINWEBER	90	ANP 198 203		(MCMS)
MUELLER-GR...	90	NP A513 557	Mueller-Groeling, Holinde, Speth	(JULI)
BARRETT	89	NC 102A 179		(SURR)
BATTY	89	NC 102A 255	+Gal	(RAL, HEBR)
CAPSTICK	89	Excited Baryons '88, p. 32		(GUEL)
LOWE	89	NC 102A 167		(BIRM)
WHITEHOUSE	89	PRL 63 1352	+	(BIRM, BOST, BRCO, BNL, CASE, BUDA, TRIU)
SIEGEL	88	PR C38 2221	+Weise	(REGE)
WORKMAN	88	PR D37 3117	+Fearing	(TRIU)
SCHNICK	87	PRL 58 1719	+Landau	(ORST)
CAPSTICK	86	PR D34 2809	+Isgur	(TNTO)
JENNINGS	86	PL B176 229		(TRIU)
MALTMAN	86	PR D34 1372	+Isgur	(LANL, TNTO)
ZHONG	86	PL B171 471	+Thomas, Jennings, Barrett	(ADLD, TRIU, SURR)
BURKHARDT	85	NP A440 653	+Lowe, Rosenthal	(NOTT, BIRM, WMIU)
DAREWYCH	85	PR D32 1765	+Koniuk, Isgur	(YORKC, TNTO)
VEIT	85	PR D31 1033	+Jennings, Thomas, Barrett	(TRIU, ADLD, SURR)
KIANG	84	PR C30 1638	+Kumar, Nogami, VanDijk	(DALH, MCMS)
MILLER	84			(LOUC)
Conf. Intersections between Particle and Nuclear Physics, p. 783				
VANDIJK	84	PR D30 937		(MCMS)
VEIT	84	PL 137B 415	+Jennings, Barrett, Thomas	(TRIU, SURR, CERN)
DALITZ	82		+McGinley, Belyea, Anthony	(OXFTP)
Heidelberg Conf., p. 201				
DALITZ	81		+McGinley	(OXFTP)
Low and Intermediate Energy Kaon-Nucleon Physics, p.381				
MARTIN	81B	Low and Intermediate Energy Kaon-Nucleon Phys., p. 97		(DURH)
OADES	77	NC 42A 462	+Rasche	(AARH, ZURI)
SHAW	73	Purdue Conf. 417		(UCI)
BARBARO-...	72	LBL-555	Barbaro-Galtieri	(LBL)
DOBSON	72	PR D6 3256	+McElhaney	(HAWA)
RAJASEKA...	72	PR D5 610	Rajasekaran	(TATA)
Earlier papers also cited in RAJASEKARAN 72.				
CLINE	71	PRL 26 1194	+Laumann, Mapp	(WISC)
MARTIN	71	PL 35B 62	+Martin, Ross	(DURH, LOUC, RHEL)
DALITZ	67	PR 153 1617	+Wong, Rajasekaran	(OXFTP, BOMB)
DONALD	66	PL 22 711	+Edwards, Lys, Nisar, Moore	(LIVP)
KADYK	66	PRL 17 599	+Oren, Goldhaber, Goldhaber, Trilling	(LRL)
ABRAMS	65	PR 139B 454	+Sechi-Zorn	(UMD)

$\Lambda(1520)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

Discovered by FERRO-LUZZI 62; the elaboration in WATSON 63 is the classic paper on the Breit-Wigner analysis of a multichannel resonance.

The measurements of the mass, width, and elasticity published before 1975 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

Production and formation experiments agree quite well, so they are listed together here.

$\Lambda(1520)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1519.5 ±1.0 OUR ESTIMATE					
1519.50±0.18 OUR AVERAGE					
1517.3 ±1.5	300	BARBER	80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
1519 ±1		GOPAL	80	DPWA	$\overline{K} N \rightarrow \overline{K} N$
1517.8 ±1.2	5k	BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
1520.0 ±0.5		ALSTON-...	78	DPWA	$\overline{K} N \rightarrow \overline{K} N$
1519.7 ±0.3	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
1519 ±1		GOPAL	77	DPWA	$\overline{K} N$ multichannel
1519.4 ±0.3	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
15.6 ±1.0 OUR ESTIMATE					
15.59±0.27 OUR AVERAGE					
16.3 ±3.3	300	BARBER	80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
16 ±1		GOPAL	80	DPWA	$\overline{K} N \rightarrow \overline{K} N$
14 ±3	677	[1] BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
15.4 ±0.5		ALSTON-...	78	DPWA	$\overline{K} N \rightarrow \overline{K} N$
16.3 ±0.5	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
15.0 ±0.5		GOPAL	77	DPWA	$\overline{K} N$ multichannel
15.5 ±1.6	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	45 ± 1%
Γ_2	$\Sigma\pi$	42 ± 1%
Γ_3	$\Lambda\pi\pi$	10 ± 1%
Γ_4	$\Sigma(1385)\pi$	
Γ_5	$\Sigma(1385)\pi(\rightarrow \Lambda\pi\pi)$	
Γ_6	$\Lambda(\pi\pi)_{S\text{-wave}}$	
Γ_7	$\Sigma\pi\pi$	0.9 ± 0.1%
Γ_8	$\Lambda\gamma$	0.8 ± 0.2%
Γ_9	$\Sigma^0\gamma$	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 24 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 16.5 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccccc}
x_2 & -63 \\
x_3 & -32 & -33 \\
x_7 & -4 & -3 & -1 \\
x_8 & -9 & -8 & -4 & 0 \\
x_9 & -24 & -21 & -10 & -1 & -2 \\
\hline
 & x_1 & x_2 & x_3 & x_7 & x_8
\end{array}$$

$\Lambda(1520)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

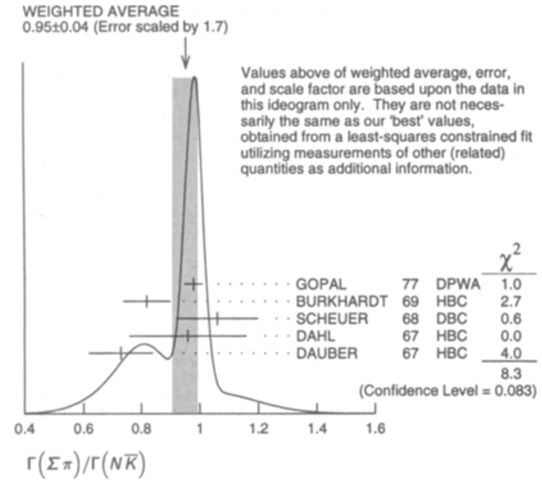
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.45 ±0.01 OUR ESTIMATE				
0.448±0.007 OUR FIT Error includes scale factor of 1.2.				
0.455±0.011 OUR AVERAGE				
0.47 ±0.02	GOPAL	80	DPWA	$\overline{K} N \rightarrow \overline{K} N$
0.45 ±0.03	ALSTON-...	78	DPWA	$\overline{K} N \rightarrow \overline{K} N$
0.448±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.01	GOPAL	77	DPWA	See GOPAL 80
0.42	MAST	76	HBC	$K^- p \rightarrow \overline{K}^0 n$

$\Gamma(\Sigma\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.42 ±0.01 OUR ESTIMATE				
0.421±0.007 OUR FIT Error includes scale factor of 1.2.				
0.423±0.011 OUR AVERAGE				
0.426±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.418±0.017	BARBARO-...	69B	HBC	$K^- p$ 0.28–0.45 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.46	KIM	71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$ Γ_2/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.940±0.026 OUR FIT Error includes scale factor of 1.3.				
0.95 ±0.04 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.				
0.98 ±0.03	[2] GOPAL	77	DPWA	$\overline{K} N$ multichannel
0.82 ±0.08	BURKHARDT	69	HBC	$K^- p$ 0.8–1.2 GeV/c
1.06 ±0.14	SCHEUER	68	DBC	$K^- N$ 3 GeV/c
0.96 ±0.20	DAHL	67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.73 ±0.11	DAUBER	67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.06 ±0.12	BERTHON	74	HBC	Quasi-2-body σ
1.72 ±0.78	MUSGRAVE	65	HBC	



$\Gamma(\Lambda\pi\pi)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.10 ±0.01 OUR ESTIMATE			
0.095±0.005 OUR FIT Error includes scale factor of 1.2.			
0.096±0.008 OUR AVERAGE Error includes scale factor of 1.6.			
0.091±0.006	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.11 ±0.01	[3] MAST 73B	IPWA	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Lambda\pi\pi)/\Gamma(N\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.213±0.012 OUR FIT Error includes scale factor of 1.2.			
0.202±0.021 OUR AVERAGE			
0.22 ±0.03	BURKHARDT 69	HBC	$K^- p$ 0.8–1.2 GeV/c
0.19 ±0.04	SCHEUER 68	DBC	$K^- N$ 3 GeV/c
0.17 ±0.05	DAHL 67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.21 ±0.18	DAUBER 67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.27 ±0.13	BERTHON 74	HBC	Quasi-2-body σ
0.2	KIM 71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
4.42±0.25 OUR FIT Error includes scale factor of 1.2.			
3.9 ±0.6 OUR AVERAGE			
3.9 ±1.0	UHLIG 67	HBC	$K^- p$ 0.9–1.0 GeV/c
3.3 ±1.1	BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
4.5 ±1.0	ARMENTEROS 65C	HBC	

$\Gamma(\Sigma(1385)\pi)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.041±0.005	CHAN 72	HBC	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Sigma(1385)\pi(\rightarrow \Lambda\pi\pi))/\Gamma(\Lambda\pi\pi)$ — Γ_5/Γ_3

The $\Lambda\pi\pi$ mode is largely due to $\Sigma(1385)\pi$. Only the values of $(\Sigma(1385)\pi)$ / $(\Lambda 2\pi)$ given by MAST 73B and CORDEN 75 are based on real 3-body partial-wave analyses. The discrepancy between the two results is essentially due to the different hypotheses made concerning the shape of the $(\pi\pi)_{S\text{-wave}}$ state.

VALUE	DOCUMENT ID	TECN	COMMENT
0.58±0.22	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.82±0.10	[4] MAST 73B	IPWA	$K^- p \rightarrow \Lambda\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.39±0.10	[5] BURKHARDT 71	HBC	$K^- p \rightarrow (\Lambda\pi\pi)\pi$

$\Gamma(\Lambda(\pi\pi)_{S\text{-wave}})/\Gamma(\Lambda\pi\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.20±0.08	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ — Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.009 ±0.001 OUR ESTIMATE			
0.0086±0.0005 OUR FIT			
0.0086±0.0005 OUR AVERAGE			
0.007 ±0.002	[6] CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.0085±0.0006	[7] MAST 73	MPWA	$K^- p \rightarrow \Sigma\pi\pi$
0.010 ±0.0015	BARBARO-... 69B	HBC	$K^- p$ 0.28–0.45 GeV/c

$\Gamma(\Lambda\gamma)/\Gamma_{\rm total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.008 ±0.002 OUR ESTIMATE				
0.0079±0.0014 OUR FIT				
0.0080±0.0014	238	MAST 68B	HBC	Using $\Gamma(N\overline{K})/\Gamma_{\rm total}$ = 0.45

$\Gamma(\Sigma^0\gamma)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0195±0.0034 OUR FIT			
0.02 ±0.0035	[8] MAST 68B	HBC	Not measured; see note

Λ(1520) FOOTNOTES

[1] From the best-resolution sample of $\Lambda\pi\pi$ events only.

[2] The $\overline{K}N \rightarrow \Sigma\pi$ amplitude at resonance is +0.46 ± 0.01.

[3] Assumes $\Gamma(N\overline{K})/\Gamma_{\rm total}$ = 0.46 ± 0.02.

[4] Both $\Sigma(1385)\pi$ DS_{03} and $\Sigma(\pi\pi)$ DP_{03} contribute.

[5] The central bin (1514–1524 MeV) gives 0.74 ± 0.10; other bins are lower by 2-to-5 standard deviations.

[6] Much of the $\Sigma\pi\pi$ decay proceeds via $\Sigma(1385)\pi$.

[7] Assumes $\Gamma(N\overline{K})/\Gamma_{\rm total}$ = 0.46.

[8] Calculated from $\Gamma(\Lambda\gamma)/\Gamma_{\rm total}$, assuming SU(3). Needed to constrain the sum of all the branching ratios to be unity.

Λ(1520) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
BARBER	80D	ZPHY C7 17	+Dainton, Lee, Marshall+	(DARE, LANC, SHEF)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
BARLAG	79	NP B149 220	+Blokzijl, Jongejans+	(AMST, CERN, NIJM, OXF)
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MAST	76	PR D14 13	+Alston-Garnjost, Bangerter+	(LBL)
CORDEN	75	NP B84 306	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
MAST	73B	PR D7 5	+Bangerter, Alston-Garnjost+	(LBL) IJP
CHAN	72	PRL 28 256	+Button-Shafer, Hertzbach, Kofler+	(MASA, YALE)
BURKHARDT	71	NP B27 64	+Filthuth, Kluge+	(HEID, CERN, SACL)
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BARBARO-...	69B	Lund Conf. 352	Barbaro-Galtieri, Bangerter, Mast, Tripp	(LRL)
Also	70	Duke Conf. 95	Tripp	(LRL)
BURKHARDT	69	NP B14 106	+Filthuth, Kluge+	(HEID, EFI, CERN, SACL)
MAST	68B	PRL 21 1715	+Alston-Garnjost, Bangerter, Galtieri+	(LRL)
SCHEUER	68	NP B8 503	+Merrill, Verglas, DeWitt+	(SABRE Collab.)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
DAUBER	67	PL 24B 525	+Malamud, Schlein, Slater, Stork	(UCLA)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL)
MUSGRAVE	65	NC 35 735	+Petmezas+	(BIRM, CERN, EPOL, LOIC, SACL)
WATSON	63	PR 131 2248	+Ferro-Luzzi, Tripp	(LRL) IJP
FERRO-LUZZI	62	PRL 8 28	+Tripp, Watson	(LRL) IJP

$\Lambda(1600)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

See also the $\Lambda(1810)$ P_{01}. There are quite possibly two P_{01} states in this region.

Λ(1600) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1560 to 1700 (≈ 1600) OUR ESTIMATE			
1568± 20	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1703±100	ALSTON-... 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1573± 25	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1596± 6	KANE 74	DPWA	$K^- p \rightarrow \Sigma\pi$
1620± 10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1572 or 1617	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1646± 7	[2] CARROLL 76	DPWA	Isospin-0 total σ
1570	KIM 71	DPWA	K-matrix analysis

Λ(1600) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE			
116± 20	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
593±200	ALSTON-... 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
147± 50	GOPAL 77	DPWA	$\overline{K}N$ multichannel
175± 20	KANE 74	DPWA	$K^- p \rightarrow \Sigma\pi$
60± 10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
247 or 271	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
20	[2] CARROLL 76	DPWA	Isospin-0 total σ
50	KIM 71	DPWA	K-matrix analysis

Λ(1600) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–30 %
Γ_2	$\Sigma\pi$	10–60 %

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1600)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.30 OUR ESTIMATE				
0.23±0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.25±0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.04	GOPAL	77	DPWA	See GOPAL 80
0.30 or 0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1600) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.33±0.11	KANE	74	DPWA	$K^-p \to \Sigma\pi$
0.28±0.09	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.39 or −0.39	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$

$\Lambda(1600)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] A total cross-section bump with $(J+1/2)\ \Gamma_{\text{el}}\ /\ \Gamma_{\text{total}} = 0.04$.

$\Lambda(1600)$ REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEIDH, MPIM) IJP
KANE 74 LBL-2452 (LBL) IJP
LANGBEIN 72 NP B47 477 +Wagner (MPIM) IJP
KIM 71 PRL 27 356 (HARV) IJP

$\Lambda(1670)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1670)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1660 to 1680 (≈ 1670) OUR ESTIMATE				
1670.8±1.7	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
1667 ±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1671 ±3	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1675 ±2	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
1679 ±1	KANE	74	DPWA	$K^-p \to \Sigma\pi$
1665 ±5	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1669 ±2	ABAEV	96	DPWA	$\pi^-p \to \eta n$
1664	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
25 to 50 (≈ 35) OUR ESTIMATE				
34.1± 3.7	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
29 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
29 ± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
45 ±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46 ± 5	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
40 ± 3	KANE	74	DPWA	$K^-p \to \Sigma\pi$
19 ± 5	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
21 ± 4	ABAEV	96	DPWA	$\pi^-p \to \eta n$
12	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–25 %
Γ_2	$\Sigma\pi$	20–60 %
Γ_3	$\Lambda\eta$	15–35 %
Γ_4	$\Sigma(1385)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.25 OUR ESTIMATE				
0.18±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.17±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20±0.03	GOPAL	77	DPWA	See GOPAL 80
0.15	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26±0.02	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
−0.31±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
−0.23±0.03	LONDON	75	HLBC	$K^-p \to \Sigma^0\pi^0$
−0.27±0.02	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1670) \to \Lambda\eta$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.20±0.05	BAXTER	73	DPWA	$K^-p \to$ neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.06	ABAEV	96	DPWA	$\pi^-p \to \eta n$
0.24	KIM	71	DPWA	K-matrix analysis
0.26	ARMENTEROS	69C	HBC	
0.20 or 0.23	BERLEY	65	HBC	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.18±0.05	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$\Lambda(1670)$ FOOTNOTES

[1] MARTIN 77 obtains identical resonance parameters from a T-matrix pole and from a Breit-Wigner fit.

$\Lambda(1670)$ REFERENCES

ABAEV 96 PR C53 385 +Nefkens (UCLA)
KOISO 85 NP A433 619 +Sai, Yamamoto, Kofler (TOKY, MASA)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEIDH, MPIM) IJP
LONDON 75 NP B85 289 +Yu, Boyd+ (BNL, CERN, EPOL, ORSAY, TORI)
KANE 74 LBL-2452 (LBL) IJP
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
BAXTER 73 NP B67 125 +Buckingham, Corbett, Dunn+ (OXF) IJP
KIM 71 PRL 27 356 (HARV) IJP
Also 70 Duke Conf. 161 Kim (HARV) IJP
ARMENTEROS 69C Lund Paper 229 +Baillon+ (CERN, HEID, SACL) IJP
Values are quoted in LEVI-SETTI 69.
BERLEY 65 PRL 15 641 +Connolly, Hart, Rahm, Stonehill+ (BNL) IJP

$\Lambda(1690)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1690)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1685 to 1695 (≈ 1690) OUR ESTIMATE			
1695.7±2.6	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
1690 ±5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1692 ±5	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1690 ±5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1690 ±3	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
1689 ±1	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1687 or 1689	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1692 ±4	CARROLL 76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
50 to 70 (≈ 60) OUR ESTIMATE			
67.2± 5.6	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
61 ± 5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
64 ±10	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
60 ± 5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
82 ± 8	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
60 ± 4	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
62 or 62	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
38	CARROLL 76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–30 %
Γ_2	$\Sigma\pi$	20–40 %
Γ_3	$\Lambda\pi\pi$	~ 25 %
Γ_4	$\Sigma\pi\pi$	~ 20 %
Γ_5	$\Lambda\eta$	
Γ_6	$\Sigma(1385)\pi$, S-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1690)$ BRANCHING RATIOS

The sum of all the quoted branching ratios is more than 1.0. The two-body ratios are from partial-wave analyses, and thus probably are more reliable than the three-body ratios, which are determined from bumps in cross sections. Of the latter, the $\Sigma\pi\pi$ bump looks more significant. (The error given for the $\Lambda\pi\pi$ ratio looks unreasonably small.) Hardly any of the $\Sigma\pi\pi$ decay can be via $\Sigma(1385)$, for then seven times as much $\Lambda\pi\pi$ decay would be required. See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.2 to 0.3 OUR ESTIMATE			
0.23±0.03	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.22±0.03	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.24±0.03	GOPAL 77	DPWA	See GOPAL 80
0.28 or 0.26	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.34±0.02	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
−0.25±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
−0.28±0.03	LONDON 75	HLBC	$K^- p \to \Sigma^0\pi^0$
−0.28±0.02	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.30 or −0.28	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\eta$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.00±0.03	BAXTER 73	DPWA	$K^- p \to$ neutrals

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\pi\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.25±0.02	[2] BARTLEY 68	HDBC	$K^- p \to \Lambda\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.21	ARMENTEROS 68C	HDBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma(1385)\pi$, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.27±0.04	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Lambda(1690)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit. Another D_{03} Λ at 1966 MeV is also suggested by MARTIN 77, but is very uncertain.

[2] BARTLEY 68 uses only cross-section data. The enhancement is not seen by PREVOST 71.

$\Lambda(1690)$ REFERENCES

KOISO 85 NP A433 619 +Sai, Yamamoto, Kofler (TOKY, MASA)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEIDH, MPIM) IJP
LONDON 75 NP B85 289 +Yu, Boyd+ (BNL, CERN, EPOL, ORSAY, TORI)
KANE 74 LBL-2452 (LBL) IJP
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
BAXTER 73 NP B67 125 +Buckingham, Corbett, Dunn+ (OXF) IJP
PREVOST 71 Amsterdam Conf. (CERN, HEID, SACL)
ARMENTEROS 68C NP B8 216 +Baillon+ (CERN, HEID, SACL) I
BARTLEY 68 PRL 21 1111 +Chu, Dowd, Greene+ (TUFTS, FSU, BRAN) I

$\Lambda(1800)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

This is the second resonance in the S_{01} wave, the first being the $\Lambda(1670)$.

$\Lambda(1800)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1720 to 1850 (≈ 1800) OUR ESTIMATE			
1841±10	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1725±20	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1825±20	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1830±20	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1767 or 1842	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1780	KIM 71	DPWA	K-matrix analysis
1872±10	BRICMAN 70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
200 to 400 (≈ 300) OUR ESTIMATE			
228±20	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
185±20	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
230±20	GOPAL 77	DPWA	$\overline{K}N$ multichannel
70±15	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
435 or 473	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
40	KIM 71	DPWA	K-matrix analysis
100±20	BRICMAN 70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–40 %
Γ_2	$\Sigma\pi$	seen
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	seen
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1800)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.25 to 0.40 OUR ESTIMATE			
0.36±0.04	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.28±0.05	ALSTON-... 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.35±0.15	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.37±0.05	GOPAL 77	DPWA	See GOPAL 80
1.21 or 0.70	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
0.80	KIM 71	DPWA	K-matrix analysis
0.18±0.02	BRICMAN 70B	DPWA	$\overline{K}N \rightarrow \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.08±0.05	GOPAL 77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.74 or −0.43	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
0.24	KIM 71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.056±0.028	[2] CAMERON 78	DPWA	$K^- p \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow N\overline{K}^*(892)$, S=1/2, S-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.17±0.03	[2] CAMERON 78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.13±0.04	CAMERON 78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

$\Lambda(1800)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1800)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BRICMAN	70B	PL 33B 511	+Ferro-Luzzi, Lagnaux	(CERN) IJP

$\Lambda(1810)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

Almost all the recent analyses contain a P_{01} state, and sometimes two of them, but the masses, widths, and branching ratios vary greatly. See also the $\Lambda(1600)$ P_{01}.

$\Lambda(1810)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1750 to 1850 (≈ 1810) OUR ESTIMATE			
1841±20	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1853±20	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1735± 5	CARROLL 76	DPWA	Isospin-0 total σ
1746±10	PREVOST 74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$
1780±20	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1861 or 1953	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1755	KIM 71	DPWA	K-matrix analysis
1800	ARMENTEROS70	HBC	$\overline{K}N \rightarrow \overline{K}N$
1750	ARMENTEROS70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
1690±10	BARBARO-... 70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
1740	BAILEY 69	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1745	ARMENTEROS68B	HBC	$\overline{K}N \rightarrow \overline{K}N$

$\Lambda(1810)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE			
164±20	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
90±20	CAMERON 78B	DPWA	$K^- p \rightarrow N\overline{K}^*$
166±20	GOPAL 77	DPWA	$\overline{K}N$ multichannel
46±20	PREVOST 74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$
120±10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
535 or 585	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
28	CARROLL 76	DPWA	Isospin-0 total σ
35	KIM 71	DPWA	K-matrix analysis
30	ARMENTEROS70	HBC	$\overline{K}N \rightarrow \overline{K}N$
70	ARMENTEROS70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
22	BARBARO-... 70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
300	BAILEY 69	DPWA	$\overline{K}N \rightarrow \overline{K}N$
147	ARMENTEROS68B	HBC	

$\Lambda(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–50 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	30–60 %
Γ_5	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1810)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.2 to 0.5 OUR ESTIMATE			
0.24±0.04	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.36±0.05	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.21±0.04	GOPAL 77	DPWA	See GOPAL 80
0.52 or 0.49	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
0.30	KIM 71	DPWA	K-matrix analysis
0.15	ARMENTEROS70	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.55	BAILEY 69	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.4	ARMENTEROS68B	DPWA	$\overline{K}N \rightarrow \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1810) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.24±0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.25 or +0.23	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
< 0.01	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
0.17	KIM 71	DPWA	K-matrix analysis
+0.20	[2] ARMENTEROS70	DPWA	$\overline{K}N \rightarrow \Sigma\pi$
−0.13±0.03	BARBARO-... 70	DPWA	$\overline{K}N \rightarrow \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1810) \rightarrow \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.18±0.10	PREVOST 74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1810) \rightarrow N\overline{K}^*(892)$, S=1/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.14±0.03	[2] CAMERON 78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Lambda(1810) \rightarrow N\overline{K}^*(892)$, S=3/2, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.35±0.06	CAMERON 78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

$\Lambda(1810)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1810) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BAILEY	69	Thesis UCRL 50617		(LLL) IJP
ARMENTEROS	68B	NP B8 195	+Baillon+	(CERN, HEID, SACL) IJP

$\Lambda(1820)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗∗

This resonance is the cornerstone for all partial-wave analyses in this region. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

Most of the quoted errors are statistical only; the systematic errors due to the particular parametrizations used in the partial-wave analyses are not included. For this reason we do not calculate weighted averages for the mass and width.

Λ(1820) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1815 to 1825 (≈ 1820) OUR ESTIMATE				
1823±3	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1819±2	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1822±2	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1821±2	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1830	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1817 or 1819	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1820) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
70 to 90 (≈ 80) OUR ESTIMATE				
77±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
72±5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
81±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
87±3	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
82	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
76 or 76	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1820) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	55–65 %
Γ_2	$\Sigma\pi$	8–14 %
Γ_3	$\Sigma(1385)\pi$	5–10 %
Γ_4	$\Sigma(1385)\pi$, *P*-wave	
Γ_5	$\Sigma(1385)\pi$, *F*-wave	
Γ_6	$\Lambda\eta$	
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

Λ(1820) BRANCHING RATIOS

Errors quoted do not include uncertainties in the parametrizations used in the partial-wave analyses and are thus too small. See also "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.55 to 0.65 OUR ESTIMATE				
0.58±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.60±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.51	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.57±0.02	GOPAL	77	DPWA	See GOPAL 80
0.59 or 0.58	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.28±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.28±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.25 or −0.25	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Lambda\eta$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*
$-0.096^{+0.040}_{-0.020}$	RADER	73	MPWA

$\Gamma(\Sigma\pi\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
no clear signal	[2] ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, *P*-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.167±0.054	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.27 ±0.03	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, *F*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.065±0.029	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

Λ(1820) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] There is a suggestion of a bump, enough to be consistent with what is expected from $\Sigma(1385) \to \Sigma\pi$ decay.

[3] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1820) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I

$\Lambda(1830)\ D_{05}$

$I(J^P) = 0(\frac{5}{2}^-)$ Status: ∗∗∗∗

For results published before 1973 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The best evidence for this resonance is in the $\Sigma\pi$ channel.

Λ(1830) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1810 to 1830 (≈ 1830) OUR ESTIMATE				
1831±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1825±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1825± 1	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1817 or 1818	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
60 to 110 (≈ 95) OUR ESTIMATE				
100±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
94±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
119± 3	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
56 or 56	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	3–10 %
Γ_2	$\Sigma\pi$	35–75 %
Γ_3	$\Sigma(1385)\pi$	>15 %
Γ_4	$\Sigma(1385)\pi$, *D*-wave	
Γ_5	$\Lambda\eta$	

The above branching fractions are our estimates, not fits or averages.

Λ(1830) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.03 to 0.10 OUR ESTIMATE			
0.08 ± 0.03	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.02 ± 0.02	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.04 ± 0.03	GOPAL 77	DPWA	See GOPAL 80
0.04 or 0.04	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.17 ± 0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
-0.15 ± 0.01	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.17 or -0.17	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Lambda\eta$ $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN
-0.044 ± 0.020	RADER 73	MPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$+0.141 \pm 0.014$	[2] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$
$+0.13 \pm 0.03$	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$

Λ(1830) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The CAMERON 78 upper limit on G-wave decay is 0.03. The published sign has been changed to be in accord with the baryon-first convention.

Λ(1830) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)

$\Lambda(1890)$ P_{03}

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The $J^P = 3/2^+$ assignment is consistent with all available data (including polarization) and recent partial-wave analyses. The dominant inelastic modes remain unknown.

Λ(1890) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1850 to 1910 (≈ 1890) OUR ESTIMATE			
1897 ± 5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1908 ± 10	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1900 ± 5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1894 ± 10	HEMINGWAY 75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1856 or 1868	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1900	[2] NAKKASYAN 75	DPWA	$K^- p \to \Lambda\omega$

Λ(1890) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
60 to 200 (≈ 100) OUR ESTIMATE			
74 ± 10	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
119 ± 20	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
72 ± 10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
107 ± 10	HEMINGWAY 75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
191 or 193	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
100	[2] NAKKASYAN 75	DPWA	$K^- p \to \Lambda\omega$

Λ(1890) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–35 %
Γ_2	$\Sigma\pi$	3–10 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$N\overline{K}^*(892)$	seen
Γ_7	$N\overline{K}^*(892)$, $S=1/2$, P-wave	
Γ_8	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

Λ(1890) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.20 to 0.35 OUR ESTIMATE			
0.20 ± 0.02	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.34 ± 0.05	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
0.24 ± 0.04	HEMINGWAY 75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.18 ± 0.02	GOPAL 77	DPWA	See GOPAL 80
0.36 or 0.34	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.09 ± 0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$+0.15$ or $+0.14$	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Lambda\omega$ $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
seen	BACCARI 77	IPWA	$K^- p \to \Lambda\omega$
0.032	[2] NAKKASYAN 75	DPWA	$K^- p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.03	CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.126 ± 0.055	[3] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.07 ± 0.03	[3,4] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

Λ(1890) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] Found in one of two best solutions.

[3] The published sign has been changed to be in accord with the baryon-first convention.

[4] Upper limits on the P_3 and F_3 waves are each 0.03.

Λ(1890) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP

$\Lambda(2000)$

$I(J^P) = 0(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all the ambiguous resonance possibilities with a mass around 2 GeV. The proposed quantum numbers are D_3 (BARBARO-GALTIERI 70 in $\Sigma\pi$), D_3+F_5, P_3+D_5, or P_1+D_3 (BRANDSTETTER 72 in $\Lambda\omega$), and S_1 (CAMERON 78B in $N\overline{K}^*$). The first two of the above analyses should now be considered obsolete. See also NAKKASYAN 75.

$\Lambda(2000)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
≈ 2000 OUR ESTIMATE			
2030±30	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$
1935 to 1971	[1] BRANDSTET...72	DPWA	$K^- p \to \Lambda\omega$
1951 to 2034	[1] BRANDSTET...72	DPWA	$K^- p \to \Lambda\omega$
2010±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2000)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125±25	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$
180 to 240	[1] BRANDSTET...72	DPWA	(lower mass)
73 to 154	[1] BRANDSTET...72	DPWA	(higher mass)
130±50	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$
Γ_4	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Lambda(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2000) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.20±0.04	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2000) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.17 to 0.25	[1] BRANDSTET...72	DPWA	(lower mass)
0.04 to 0.15	[1] BRANDSTET...72	DPWA	(higher mass)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=1/2, S-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.12±0.03	[2] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.09±0.03	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(2000)$ FOOTNOTES

[1] The parameters quoted here are ranges from the three best fits; the lower state probably has $J \leq 3/2$, and the higher one probably has $J \leq 5/2$.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(2000)$ REFERENCES

CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
BRANDSTET...	72	NP B39 13	Brandstetter, Butterworth+	(RHEL, CDEF, SACL)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Lambda(2020)$ F_{07}

$I(J^P) = 0(\frac{7}{2}^+)$ Status: ∗

OMITTED FROM SUMMARY TABLE

In LITCHFIELD 71, need for the state rests solely on a possibly inconsistent polarization measurement at 1.784 GeV/c. HEMINGWAY 75 does not require this state. GOPAL 77 does not need it in either $N\overline{K}$ or $\Sigma\pi$. With new $K^- n$ angular distributions included, DECLAIS 77 sees it. However, this and other new data are included in GOPAL 80 and the state is not required. BACCARI 77 weakly supports it.

$\Lambda(2020)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
≈ 2020 OUR ESTIMATE			
2140	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
2117	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
2100±30	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$
2020±20	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2020)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
128	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
167	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
120±30	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$
160±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2020)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$

$\Lambda(2020)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.05	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
0.05±0.02	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2020) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.15±0.02	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2020) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.05	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2020)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Lambda(2100)$ G_{07}

$I(J^P) = 0(\frac{7}{2}^-)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and in invariant-mass distributions around 2100 MeV used to be listed in a separate entry immediately following. It may be found in our 1986 edition Physics Letters **170B** (1986).

Λ(2100) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2090 to 2110 (≈ 2100) OUR ESTIMATE			
2104±10	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
2106±30	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
2110±10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
2105±10	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
2115±10	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2094	BACCARI 77	DPWA	$K^-p \to \Lambda\omega$
2094	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
2110 or 2089	[1] NAKKASYAN 75	DPWA	$K^-p \to \Lambda\omega$

Λ(2100) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
100 to 250 (≈ 200) OUR ESTIMATE			
157±40	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
250±30	GOPAL 77	DPWA	$\overline{K}N$ multichannel
241±30	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
152±15	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
98	BACCARI 77	DPWA	$K^-p \to \Lambda\omega$
250	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
244 or 302	[1] NAKKASYAN 75	DPWA	$K^-p \to \Lambda\omega$

Λ(2100) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–35 %
Γ_2	$\Sigma\pi$	∼ 5 %
Γ_3	$\Lambda\eta$	<3 %
Γ_4	ΞK	<3 %
Γ_5	$\Lambda\omega$	<8 %
Γ_6	$N\overline{K}^*(892)$	10–20 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, G-wave	
Γ_8	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(2100) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID	TECN	COMMENT
0.25 to 0.35 OUR ESTIMATE			
0.34±0.03	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.06	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
0.31±0.03	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.29	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
0.30±0.03	GOPAL 77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Sigma\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
+0.12±0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
+0.11±0.01	KANE 74	DPWA	$K^-p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\eta$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
−0.050±0.020	RADER 73	MPWA	$K^-p \to \Lambda\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Xi K$ **$(\Gamma_1\Gamma_4)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
0.035±0.018	LITCHFIELD 71	DPWA	$K^-p \to \Xi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.003	MULLER 69B	DPWA	$K^-p \to \Xi K$
0.05	TRIPP 67	RVUE	$K^-p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\omega$ **$(\Gamma_1\Gamma_5)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
−0.070	[2] BACCARI 77	DPWA	GD_{37} wave
+0.011	[2] BACCARI 77	DPWA	GG_{17} wave
+0.008	[2] BACCARI 77	DPWA	GG_{37} wave
0.122 or 0.154	[1] NAKKASYAN 75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=3/2, D-wave **$(\Gamma_1\Gamma_8)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
+0.21±0.04	CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=1/2, G-wave **$(\Gamma_1\Gamma_7)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
−0.04±0.03	[3] CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$

Λ(2100) FOOTNOTES

[1] The NAKKASYAN 75 values are from the two best solutions found. Each has the Λ(2100) and one additional resonance (P_3 or F_5).

[2] Note that the three for BACCARI 77 entries are for three different waves.

[3] The published sign has been changed to be in accord with the baryon-first convention. The upper limit on the G_3 wave is 0.03.

Λ(2100) REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
MULLER	69B	Thesis UCRL 19372		(LRL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Lambda(2110)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982). All the references have been retained.

This resonance is in the Baryon Summary Table, but the evidence for it could be better.

Λ(2110) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2090 to 2140 (≈ 2110) OUR ESTIMATE			
2092±25	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
2125±25	CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$
2106±50	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
2140±20	DEBELLEFON 77	DPWA	$K^-p \to \Sigma\pi$
2100±50	GOPAL 77	DPWA	$\overline{K}N$ multichannel
2112± 7	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2137	BACCARI 77	DPWA	$K^-p \to \Lambda\omega$
2103	[1] NAKKASYAN 75	DPWA	$K^-p \to \Lambda\omega$

Λ(2110) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
150 to 250 (≈ 200) OUR ESTIMATE			
245±25	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
160±30	CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$
251±50	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
140±20	DEBELLEFON 77	DPWA	$K^-p \to \Sigma\pi$
200±50	GOPAL 77	DPWA	$\overline{K}N$ multichannel
190±30	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
132	BACCARI 77	DPWA	$K^-p \to \Lambda\omega$
391	[1] NAKKASYAN 75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(2110)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–25 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Lambda\omega$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$N\overline{K}^*(892)$	10–60 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(2110)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.25 OUR ESTIMATE				
0.07±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27±0.06	[2] DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07±0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.14±0.01	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
+0.20±0.03	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.10±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2110) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
0.112	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.071±0.025	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2110) \to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17±0.04	[4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Lambda(2110)$ FOOTNOTES

[1] Found in one of two best solutions.

[2] The published error of 0.6 was a misprint.

[3] The CAMERON 78 upper limit on F-wave decay is 0.03. The sign here has been changed to be in accord with the baryon-first convention.

[4] The published sign has been changed to be in accord with the baryon-first convention. The CAMERON 78B upper limits on the P_3 and F_3 waves are each 0.03.

$\Lambda(2110)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP

$\Lambda(2325)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

BACCARI 77 finds this state with either $J^P = 3/2^-$ or $3/2^+$ in a energy-dependent partial-wave analyses of $K^-p \to \Lambda\omega$ from 2070 to 2436 MeV. A subsequent semi-energy-independent analysis from threshold to 2436 MeV selects $3/2^-$. DEBELLEFON 78 (same group) also sees this state in an energy-dependent partial-wave analysis of $K^-p \to \overline{K}N$ data, and finds $J^P = 3/2^-$ or $3/2^+$. They again prefer $J^P = 3/2^-$, but only on the basis of model-dependent considerations.

$\Lambda(2325)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2325 OUR ESTIMATE				
2342±30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2327±20	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(2325)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
177±40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
160±40	BACCARI	77	IPWA	$K^-p \to \Lambda\omega$

$\Lambda(2325)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\omega$

$\Lambda(2325)$ BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.19±0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2325) \to \Lambda\omega$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	[1] BACCARI	77	IPWA	DS_{33} wave
0.05±0.02	[1] BACCARI	77	DPWA	DD_{13} wave
0.08±0.03	[1] BACCARI	77	DPWA	DD_{33} wave

$\Lambda(2325)$ FOOTNOTES

[1] Note that the three BACCARI 77 entries are for three different waves.

$\Lambda(2325)$ REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP

$\Lambda(2350)$ H_{09}

$I(J^P) = 0(\frac{9}{2}^+)$ Status: ***

DAUM 68 favors $J^P = 7/2^-$ or $9/2^+$. BRICMAN 70 favors $9/2^+$. LASINSKI 71 suggests three states in this region using a Pomeron + resonances model. There are now also three formation experiments from the College de France-Saclay group, DEBELLEFON 77, BACCARI 77, and DEBELLEFON 78, which find $9/2^+$ in energy-dependent partial-wave analyses of $\overline{K}N \to \Sigma\pi$, $\Lambda\omega$, and $N\overline{K}$.

$\Lambda(2350)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2340 to 2370 (≈ 2350) OUR ESTIMATE				
2370±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2365±20	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
2358± 6	BRICMAN	70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2372	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
2344±15	COOL	70	CNTR	K^-p, K^-d total
2360±20	LU	70	CNTR	$\gamma p \to K^+Y^*$
2340± 7	BUGG	68	CNTR	K^-p, K^-d total

Λ(2350) WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
100 to 250 (≈ 150) OUR ESTIMATE			
204±50	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
110±20	DEBELLEFON 77	DPWA	$K^- p \to \Sigma\pi$
324±30	BRICMAN 70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •			
257	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
190	COOL 70	CNTR	$K^- p$, $K^- d$ total
55	LU 70	CNTR	$\gamma p \to K^+ Y^*$
140±20	BUGG 68	CNTR	$K^- p$, $K^- d$ total

Λ(2350) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	~ 12 %
Γ_2	$\Sigma\pi$	~ 10 %
Γ_3	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

Λ(2350) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
~ 0.12 OUR ESTIMATE			
0.12±0.04	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2350) \to \Sigma\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.11±0.02	DEBELLEFON 77	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2350) \to \Lambda\omega$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.05	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$

Λ(2350) REFERENCES

DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
BACCARI 77 NC 41A 96 +Poulard, Revel, Tallini+ (SACL, CDEF) IJP
DEBELLEFON 77 NC 37A 175 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
LASINSKI 71 NP B29 125 (EFI) IJP
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
COOL 70 PR D1 1887 +Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 66 PRL 16 1228 Cool, Giacomelli, Kycia, Leontic, Lundby+ (BNL) I
LU 70 PR D2 1846 +Greenberg, Hughes, Minehart, Mori+ (YALE)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
DAUM 68 NP B7 19 +Erne, Lagnaux, Sens, Steuer, Udo (CERN) JP

Λ(2585) Bumps

$I(J^P) = 0(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Λ(2585) MASS (BUMPS)

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
≈ 2585 OUR ESTIMATE			
2585±45	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
2530±25	LU 70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) WIDTH (BUMPS)

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
300	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
150	LU 70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) DECAY MODES (BUMPS)

	Mode
Γ_1	$N\overline{K}$

Λ(2585) BRANCHING RATIOS (BUMPS)

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{\text{total}}$ **Γ_1/Γ**

J is not known, so only $(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{\text{total}}$ can be given.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
1	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
0.12±0.12	[1] BRICMAN 70	CNTR	Total, charge exchange

Λ(2585) FOOTNOTES (BUMPS)

[1] The resonance is at the end of the region analyzed — no clear signal.

Λ(2585) REFERENCES (BUMPS)

ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 66 PRL 16 1228 Cool, Giacomelli, Kycia, Leontic, Lundby+ (BNL) I
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
LU 70 PR D2 1846 +Greenberg, Hughes, Minehart, Mori+ (YALE)

Σ BARYONS
$(S = -1, I = 1)$

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ****

We have omitted some results that have been superseded by later experiments. See our earlier editions.

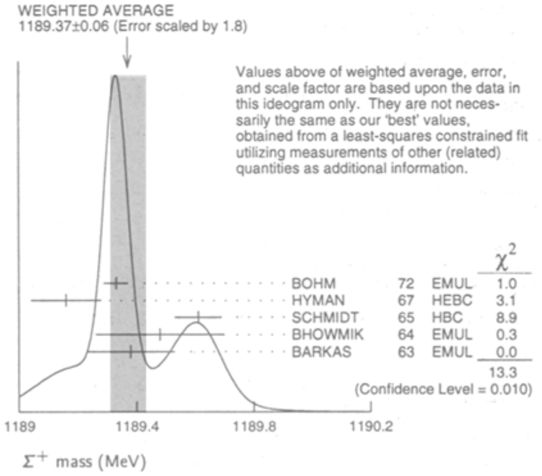
Σ^+ MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1189.37±0.07 OUR FIT	Error includes scale factor of 2.2.				
1189.37±0.06 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
1189.33±0.04	607	[1] BOHM	72	EMUL	
1189.16±0.12		HYMAN	67	HEBC	
1189.61±0.08	4205	SCHMIDT	65	HBC	See note with Λ mass
1189.48±0.22	58	[2] BHOWMIK	64	EMUL	
1189.38±0.15	144	[2] BARKAS	63	EMUL	

[1] BOHM 72 is updated with our 1973 K^-, π^-, and π^0 masses (Reviews of Modern Physics **45** No. 2 Pt. II (1973)).

[2] These masses have been raised 30 keV to take into account a 46 keV increase in the proton mass and a 21 keV decrease in the π^0 mass (note added 1967 edition, Reviews of Modern Physics **39** 1 (1967)).



Σ^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.799±0.004 OUR AVERAGE					
0.798±0.005	30k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.807±0.013	5719	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
0.83 ±0.04	526	BAKKER	71	DBC	$K^- n \rightarrow \Sigma^+ \pi^- \pi^-$
0.795±0.010	20k	EISELE	70	HBC	$K^- p$ at rest
0.803±0.008	10664	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.83 ±0.032	1300	[3] CHANG	66	HBC	
0.80 ±0.07	381	COOK	66	OSPK	
0.84 ±0.09	181	BALTAY	65	HBC	
0.76 ±0.03	900	CARAYAN...	65	HBC	
$0.749^{+0.056}_{-0.052}$	192	GRARD	62	HBC	
0.765±0.04	456	HUMPHREY	62	HBC	

[3] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).

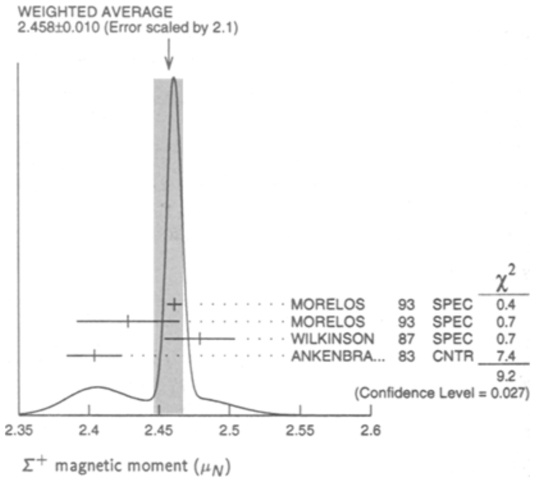
Σ^+ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings. Measurements with an error $\geq 0.1\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.458 ±0.010 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.				
2.4613±0.0034±0.0040	250k	MORELOS	93	SPEC	pCu 800 GeV
2.428 ±0.036 ±0.007	12k	[4] MORELOS	93	SPEC	pCu 800 GeV
2.479 ±0.012 ±0.022	137k	WILKINSON	87	SPEC	pBe 400 GeV
2.4040±0.0198	44k	[5] ANKENBRA...	83	CNTR	pCu 400 GeV

[4] We assume *CPT* invariance: this is (minus) the $\overline{\Sigma}^-$ magnetic moment as measured by MORELOS 93. See below for the moment difference testing *CPT*.

[5] ANKENBRANDT 83 gives the value $2.38 \pm 0.02 \mu_N$. MORELOS 93 uses the same hyperon magnet and channel and claims to determine the field integral better, leading to the revised value given here.



$(\mu_{\Sigma^+} + \mu_{\overline{\Sigma}^-}) / |\mu|_{\text{average}}$

A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.014±0.015	[6] MORELOS	93	SPEC	pCu 800 GeV

[6] This is our calculation from the MORELOS 93 measurements of the Σ^+ and $\overline{\Sigma}^-$ magnetic moments given above. The statistical error on $\mu_{\overline{\Sigma}^-}$ dominates the error here.

Σ^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p\pi^0$		(51.57 ± 0.30) %	
Γ_2	$n\pi^+$		(48.31 ± 0.30) %	
Γ_3	$p\gamma$		$(1.23 \pm 0.05) \times 10^{-3}$	
Γ_4	$n\pi^+\gamma$	[a]	$(4.5 \pm 0.5) \times 10^{-4}$	
Γ_5	$\Lambda e^+ \nu_e$		$(2.0 \pm 0.5) \times 10^{-5}$	

$\Delta S = \Delta Q$ (*SQ*) violating modes or
$\Delta S = 1$ weak neutral current (*S1*) modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_6	$n e^+ \nu_e$	*SQ*	$< 5 \times 10^{-6}$	90%
Γ_7	$n \mu^+ \nu_\mu$	*SQ*	$< 3.0 \times 10^{-5}$	90%
Γ_8	$p e^+ e^-$	*S1*	$< 7 \times 10^{-6}$	

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 14 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 7.7$ for 12 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_2 & -100 & \\ x_3 & 12 & -14 \\ \hline & x_1 & x_2 \end{array}$$

Σ^+ BRANCHING RATIOS

$\Gamma(n\pi^+)/\Gamma(N\pi)$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.4836±0.0030 OUR FIT				
0.4836±0.0030 OUR AVERAGE				
0.4828±0.0036	10k	[7] MARRAFFINO 80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.488 ±0.008	1861	NOWAK 78	HBC	
0.484 ±0.015	537	TOVEE 71	EMUL	
0.488 ±0.010	1331	BARLOUTAUD 69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.46 ±0.02	534	CHANG 66	HBC	
0.490 ±0.024	308	HUMPHREY 62	HBC	

[7] MARRAFFINO 80 actually gives $\Gamma(p\pi^0)/\Gamma(\text{total}) = 0.5172 \pm 0.0036$.

$\Gamma(p\gamma)/\Gamma(p\pi^0)$ Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.38±0.10 OUR FIT				
2.38±0.10 OUR AVERAGE				
2.32±0.11±0.10	32k	TIMM 95	E761	Σ^+ 375 GeV
$2.81\pm0.39^{+0.21}_{-0.43}$	408	HESSEY 89	CNTR	$K^- p \to \Sigma^+\pi^-$ at rest
2.52±0.28	190	[8] KOBAYASHI 87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$2.46^{+0.30}_{-0.35}$	155	BIAGI 85	CNTR	CERN hyperon beam
2.11±0.38	46	MANZ 80	HBC	$K^- p \to \Sigma^+\pi^-$
2.1 ±0.3	45	ANG 69B	HBC	$K^- p$ at rest
2.76±0.51	31	GERSHWIN 69B	HBC	$K - p \to \Sigma^+\pi^-$
3.7 ±0.8	24	BAZIN 65	HBC	$K^- p$ at rest

[8] KOBAYASHI 87 actually gives $\Gamma(p\gamma)/\Gamma(\text{total}) = (1.30 \pm 0.15) \times 10^{-3}$.

$\Gamma(n\pi^+\gamma)/\Gamma(n\pi^+)$ Γ_4/Γ_2

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.93±0.10	180	EBENHOH 73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.27±0.05	29	ANG 69B	HBC	$\pi^+ < 110$ MeV/c
~ 1.8		BAZIN 65B	HBC	$\pi^+ < 116$ MeV/c

$\Gamma(\Lambda e^+\nu_e)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID	TECN	COMMENT
2.0±0.5 OUR AVERAGE				
1.6±0.7	5	BALTAY 69	HBC	$K^- p$ at rest
2.9±1.0	10	EISELE 69	HBC	$K^- p$ at rest
2.0±0.8	6	BARASH 67	HBC	$K^- p$ at rest

$\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ Γ_6/Γ_2

Test of $\Delta S = \Delta Q$ rule. Experiments with an effective denominator less than 100,000 have been omitted.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.1 x 10^{-5} OUR LIMIT				Our 90% CL limit = (2.3 events)/(effective denominator sum). [Number of events increased to 2.3 for a 90% confidence level.]
111000	0	[9] EBENHOH 74	HBC	$K^- p$ at rest
105000	0	[9] SECHI-ZORN 73	HBC	$K^- p$ at rest

[9] Effective denominator calculated by us.

$\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ Γ_7/Γ_2

Test of $\Delta S = \Delta Q$ rule.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID	TECN
< 6.2 x 10^{-5} OUR LIMIT			Our 90% CL limit = (6.7 events)/(effective denominator sum). [Number of events increased to 6.7 for a 90% confidence level.]
33800	0	BAGGETT 69B	HBC
62000	2	[10] EISELE 69B	HBC
10150	0	[11] COURANT 64	HBC
1710	0	[11] NAUENBERG 64	HBC
120	1	GALTIERI 62	EMUL

[10] Effective denominator calculated by us.

[11] Effective denominator taken from EISELE 67.

$\Gamma(pe^+e^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-6})	DOCUMENT ID	TECN	COMMENT
<7	[12] ANG 69B	HBC	$K^- p$ at rest

[12] ANG 69B found three pe^+e^- events in agreement with $\gamma \to e^+e^-$ conversion from $\Sigma^+ \to p\gamma$. The limit given here is for neutral currents.

$\Gamma(\Sigma^+ \to ne^+\nu_e)/\Gamma(\Sigma^- \to ne^-\overline{\nu}_e)$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.009 OUR LIMIT					Our 90% CL limit, using $\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ above.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.019	90	0	EBENHOH 74	HBC	$K^- p$ at rest
<0.018	90	0	SECHI-ZORN 73	HBC	$K^- p$ at rest
<0.12	95	0	COLE 71	HBC	$K^- p$ at rest
<0.03	90	0	EISELE 69B	HBC	See EBENHOH 74

$\Gamma(\Sigma^+ \to n\mu^+\nu_\mu)/\Gamma(\Sigma^- \to n\mu^-\overline{\nu}_\mu)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<0.12 OUR LIMIT				Our 90% CL limit, using $\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ above.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.06^{+0.045}_{-0.03}$	2	EISELE 69B	HBC	$K^- p$ at rest

$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$

Test of $\Delta S = \Delta Q$ rule.

VALUE	EVTS	DOCUMENT ID	TECN
<0.043 OUR LIMIT			Our 90% CL limit, using $\left[\Gamma(ne^+\nu_e) + \Gamma(n\mu^+\nu_\mu)\right]/\Gamma(n\pi^+)$.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.08	1	NORTON 69	HBC
<0.034	0	BAGGETT 67	HBC

Σ^+ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. A few early results have been omitted.

α_0 FOR $\Sigma^+ \to p\pi^0$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.980^{+0.017}_{-0.015}$ OUR FIT				
$-0.980^{+0.017}_{-0.013}$ OUR AVERAGE				
$-0.945^{+0.055}_{-0.042}$	1259	[13] LIPMAN 73	OSPK	$\pi^+ p \to \Sigma^+$
−0.940±0.045	16k	BELLAMY 72	ASPK	$\pi^+ p \to \Sigma^+ K^+$
$-0.98\ ^{+0.05}_{-0.02}$	1335	[14] HARRIS 70	OSPK	$\pi^+ p \to \Sigma^+ K^+$
−0.999±0.022	32k	BANGERTER 69	HBC	$K^- p$ 0.4 GeV/c

[13] Decay protons scattered off aluminum.

[14] Decay protons scattered off carbon.

ϕ_0 ANGLE FOR $\Sigma^+ \to p\pi^0$ $(\tan\phi_0 = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
36 ±34 OUR AVERAGE				
$38.1^{+35.7}_{-37.1}$	1259	[15] LIPMAN 73	OSPK	$\pi^+ p \to \Sigma^+ K^+$
22 ±90		[16] HARRIS 70	OSPK	$\pi^+ p \to \Sigma^+ K^+$

[15] Decay proton scattered off aluminum.

[16] Decay protons scattered off carbon.

α_+ / α_0

Older results have been omitted.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.069±0.013 OUR FIT				
−0.073±0.021	23k	MARRAFFINO 80	HBC	$K^- p$ 0.42–0.5 GeV/c

α_+ FOR $\Sigma^+ \to n\pi^+$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.068±0.013 OUR FIT				
0.066±0.016 OUR AVERAGE				
0.037±0.049	4101	BERLEY 70B	HBC	
0.069±0.017	35k	BANGERTER 69	HBC	$K^- p$ 0.4 GeV/c

ϕ_+ ANGLE FOR $\Sigma^+ \to n\pi^+$ $(\tan\phi_+ = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
167±20 OUR AVERAGE				Error includes scale factor of 1.1.
184±24	1054	[17] BERLEY 70B	HBC	
143±29	560	BANGERTER 69B	HBC	$K^- p$ 0.4 GeV/c

[17] Changed from 176 to 184° to agree with our sign convention.

α_γ FOR $\Sigma^+ \to p\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.76 ±0.08 OUR AVERAGE				
−0.720±0.086±0.045	35k	[18] FOUCHER 92	SPEC	Σ^+ 375 GeV
−0.86 ±0.13 ±0.04	190	KOBAYASHI 87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$-0.53\ ^{+0.38}_{-0.36}$	46	MANZ 80	HBC	$K^- p \to \Sigma^+\pi^-$
$-1.03\ ^{+0.52}_{-0.42}$	61	GERSHWIN 69B	HBC	$K^- p \to \Sigma^+\pi^-$

[18] See TIMM 95 for a detailed description of the analysis.

Σ^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

TIMM	95	PR D51 4638	+Albuquerque, Bondar+	(FNAL E761 Collab.)
MORELOS	93	PRL 71 3417	+Albuquerque, Bondar, Carrigan+	(FNAL E761 Collab.)
FOUCHER	92	PRL 68 3004	+Albuquerque, Bondar+	(FNAL E761 Collab.)
HESSEY	89	ZPHY C42 175	+Booth, Fickinger, Gall+	(BNL-811 Collab.)
KOBAYASHI	87	PRL 59 868	+Haba, Homma, Kawai, Miyake+	(KYOT)
WILKINSON	87	PRL 58 855	+Handler+	(WISC, MICH, RUTG, MINN)
BIAGI	85	ZPHY C28 495	+Bourquin+	(CERN WA62 Collab.)
ANKENBRA...	83	PRL 51 863	Ankenbrandt, Berge+	(FNAL, IOWA, ISU, YALE)
MANZ	80	PL 96B 217	+Reucroft, Settles, Wolf+	(MPIM, VAND)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
NOWAK	78	NP B139 61	+Armstrong, Davis+	(LOUC, BELG, DURH, WARS)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEIDT)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEIDT)
LIPMAN	73	PL 43B 89	+Uto, Walker, Montgomery+	(RHEL, SUSS, LOWC)
PDG	73	RMP 45 No. 2 Pt. II	Lasinski, Barbaro-Galtieri, Kelly+	(LBL, BRAN, CERN+)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BELLAMY	72	PL 39B 299	+Anderson, Crawford+	(LOWC, RHEL, SUSS)
BOHM	72	NP B48 1	+	(BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
Also	73	IIHE-73.2 Nov	Bohm	(BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
TOVEE	71	NP B33 493	+	(LOUC, KIDR, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
HARRIS	70	PRL 24 165	+Overseth, Pondrom, Dettmann	(MICH, WISC)
PDG	70	RMP 42 No. 1	Barbaro-Galtieri, Derenzo, Price+	(LRL, BRAN, CERN+)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69B	Thesis MDDP-TR-973		(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	Thesis UCRL 19244		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
Also	64	PRL 13 291	Willis, Courant+	(BNL, CERN, HEID, UMD)
EISELE	69B	ZPHY 221 401	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
GERSHWIN	69B	PR 188 2077	+Alston-Garnjost, Bangerter+	(LRL)
Also	69	Thesis UCRL 19246	Gershwin	(LRL)
NORTON	69	Thesis Nevis 175		(COLU)
BAGGETT	67	PRL 19 1458	+Day, Glasser, Kehoe, Knop+	(UMD)
Also	68	Vienna Abs. 374	Baggett, Kehoe	(UMD)
Also	68B	Private Comm.	Baggett	(UMD)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
EISELE	67	ZPHY 205 409	+Engelmann, Filthuth, Folish, Hepp+	(HEID)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
PDG	67	RMP 39 1	Rosenfeld, Barbaro-Galtieri, Podolsky+	(LRL, CERN, YALE)
CHANG	66	PR 151 1081		(COLU)
Also	65	Thesis Nevis 145	Chang	(COLU)
COOK	66	PRL 17 223	+Ewart, Masek, Orr, Platner	(WASH)
BALTAY	65	PR 140B 1027	+Sandweiss, Culwick, Kopp+	(YALE, BNL)
BAZIN	65	PRL 14 154	+Blumenfeld, Nauenberg+	(PRIN, COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
CARAYAN...	65	PR 138B 433	Carayannopoulos, Tautfest, Willmann	(PURD)
SCHMIDT	65	PR 140B 1328		(COLU)
BHOWMIK	64	NP 53 22	+Jain, Mathur, Lakshmi	(DELH)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
NAUENBERG	64	PRL 12 679	+Marateck+	(COLU, RUTG, PRIN)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
Also	61	Thesis UCRL 9450	Dyer	(LRL)
GALTIERI	62	PRL 9 26	+Barkas, Heckman, Patrick, Smith	(LRL)
GRARD	62	PR 127 607	+Smith	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\boxed{\Sigma^0}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

Σ^0 MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1192.642±0.024 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1192.65 ±0.020±0.014	3327	[1] WANG 97	SPEC	$\Sigma^0 \rightarrow \Lambda\gamma \rightarrow (p\pi^-)(e^+e^-)$

[1] This WANG 97 result is redundant with the Σ^0-Λ mass-difference measurement below.

$m_{\Sigma^-} - m_{\Sigma^0}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.807±0.035 OUR FIT Error includes scale factor of 1.1.				
4.86 ±0.08 OUR AVERAGE Error includes scale factor of 1.2.				
4.87 ±0.12	37	DOSCH 65	HBC	
5.01 ±0.12	12	SCHMIDT 65	HBC	See note with Λ mass
4.75 ±0.1	18	BURNSTEIN 64	HBC	

$m_{\Sigma^0} - m_{\Lambda}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
76.959±0.023 OUR FIT				
76.966±0.020±0.013	3327	WANG 97	SPEC	$\Sigma^0 \rightarrow \Lambda\gamma \rightarrow (p\pi^-)(e^+e^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
76.23 ±0.55	109	COLAS 75	HLBC	$\Sigma^0 \rightarrow \Lambda\gamma$
76.63 ±0.28	208	SCHMIDT 65	HBC	See note with Λ mass

Σ^0 MEAN LIFE

These lifetimes are deduced from measurements of the cross sections for the Primakoff process $\Lambda \rightarrow \Sigma^0$ in nuclear Coulomb fields. An alternative expression of the same information is the Σ^0-Λ transition magnetic moment given in the following section. The relation is $(\mu_{\Sigma\Lambda}/\mu_N)^2\ \tau = 1.92951 \times 10^{-19}$ s (see DEVLIN 86).

VALUE (10^{-20} s)	*DOCUMENT ID*	*TECN*	*COMMENT*
7.4±0.7 OUR EVALUATION	Using $\mu_{\Sigma\Lambda}$ (see the above note).		
$6.5^{+1.7}_{-1.1}$	[2] DEVLIN 86	SPEC	Primakoff effect
7.6±0.5±0.7	[3] PETERSEN 86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.8±1.3	[2] DYDAK 77	SPEC	See DEVLIN 86

[2] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.

[3] An additional uncertainty of the Primakoff formalism is estimated to be < 5%.

$|\mu(\Sigma^0 \rightarrow \Lambda)|$ TRANSITION MAGNETIC MOMENT

See the note in the Σ^0 mean-life section above. Also, see the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	*DOCUMENT ID*	*TECN*	*COMMENT*
1.61±0.08 OUR AVERAGE			
$1.72^{+0.17}_{-0.19}$	[4] DEVLIN 86	SPEC	Primakoff effect
1.59±0.05±0.07	[5] PETERSEN 86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.82^{+0.25}_{-0.18}$	[4] DYDAK 77	SPEC	See DEVLIN 86

[4] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.

[5] An additional uncertainty of the Primakoff formalism is estimated to be < 2.5%.

Σ^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\gamma$	100 %	
Γ_2	$\Lambda\gamma\gamma$	< 3 %	90%
Γ_3	Λe^+e^-	[a] 5×10^{-3}	

[a] A theoretical value using QED.

Σ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*
<0.03	90	COLAS 75	HLBC

$\Gamma(\Lambda e^+e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*	*COMMENT*
0.00545	FEINBERG 58	Theoretical QED calculation

Σ^0 REFERENCES

WANG	97	PR D56 2544	+Hartouni, Kreisler+	(BNL-E766 Collab.)
DEVLIN	86	PR D34 1626	+Petersen, Beretvas	(RUTG)
PETERSEN	86	PRL 57 949	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
DYDAK	77	NP B118 1	+Navarria, Overseth, Steffen+	(CERN, DORT, HEIDH)
COLAS	75	NP B91 253	+Farwell, Ferrer, Six	(ORSAY)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
FEINBERG	58	PR 109 1019		(BNL)

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Σ^- MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1197.449±0.030 OUR FIT	Error includes scale factor of 1.2.				
1197.45 ±0.04 OUR AVERAGE	Error includes scale factor of 1.2.				
1197.417±0.040		GUREV	93	SPEC	Σ^- C atom, crystal diff.
1197.532±0.057		GALL	88	CNTR	Σ^- Pb, Σ^- W atoms
1197.43 ±0.08	3000	SCHMIDT	65	HBC	See note with Λ mass
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1197.24 ±0.15		[1] DUGAN	75	CNTR	Exotic atoms

[1] GALL 88 concludes that the DUGAN 75 mass needs to be reevaluated.

$m_{\Sigma^-} - m_{\Sigma^+}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*
8.08±0.08 OUR FIT	Error includes scale factor of 1.9.			
8.09±0.16 OUR AVERAGE				
7.91±0.23	86	BOHM	72	EMUL
8.25±0.25	2500	DOSCH	65	HBC
8.25±0.40	87	BARKAS	63	EMUL

$m_{\Sigma^-} - m_\Lambda$

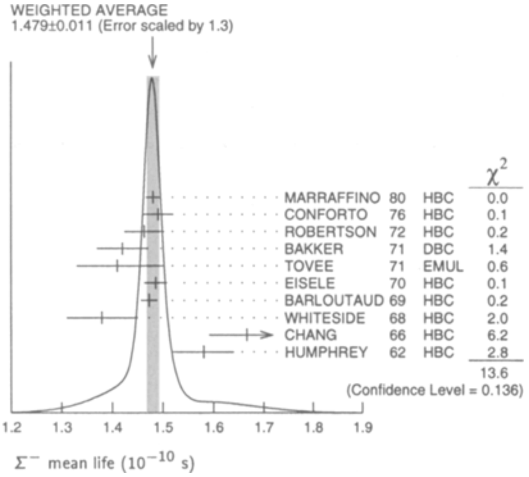
VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
81.766±0.030 OUR FIT	Error includes scale factor of 1.2.				
81.69 ±0.07 OUR AVERAGE					
81.64 ±0.09	2279	HEPP	68	HBC	
81.80 ±0.13	85	SCHMIDT	65	HBC	See note with Λ mass
81.70 ±0.19		BURNSTEIN	64	HBC	

Σ^- MEAN LIFE

Measurements with an error $\geq 0.2 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.479±0.011 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
1.480±0.014	16k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
1.49 ±0.03	8437	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
1.463±0.039	2400	ROBERTSON	72	HBC	$K^- p$ 0.25 GeV/c
1.42 ±0.05	1383	BAKKER	71	DBC	$K^- N \to \Sigma^- \pi\pi$
1.41 $^{+0.09}_{-0.08}$		TOVEE	71	EMUL	
1.485±0.022	100k	EISELE	70	HBC	$K^- p$ at rest
1.472±0.016	10k	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
1.38 ±0.07	506	WHITESIDE	68	HBC	$K^- p$ at rest
1.666±0.075	3267	[2] CHANG	66	HBC	$K^- p$ at rest
1.58 ±0.06	1208	HUMPHREY	62	HBC	$K^- p$ at rest

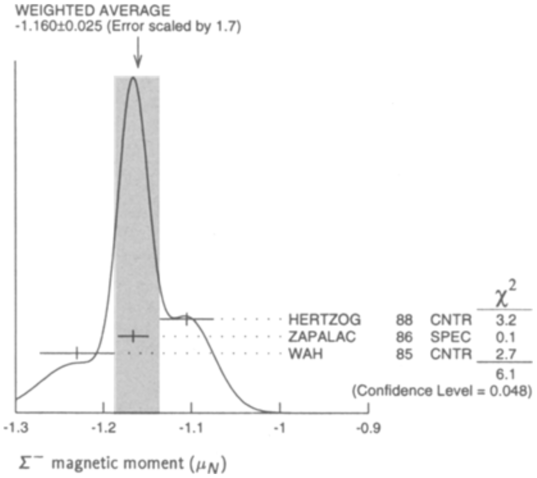
[2] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).



Σ^- MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−1.160±0.025 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
−1.105±0.029±0.010		HERTZOG	88	CNTR	Σ^- Pb, Σ^- W atoms
−1.166±0.014±0.010	671k	ZAPALAC	86	SPEC	$n e^- \nu$, $n\pi^-$ decays
−1.23 ±0.03 ±0.03		WAH	85	CNTR	$p\mathrm{Cu} \to \Sigma^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.89 ±0.14	516k	DECK	83	SPEC	$p\mathrm{Be} \to \Sigma^- X$



Σ^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$n\pi^-$	(99.848±0.005) %
Γ_2	$n\pi^-\gamma$	[a] (4.6 ±0.6) × 10^{-4}
Γ_3	$n e^- \overline{\nu}_e$	(1.017±0.034) × 10^{-3}
Γ_4	$n \mu^- \overline{\nu}_\mu$	(4.5 ±0.4) × 10^{-4}
Γ_5	$\Lambda e^- \overline{\nu}_e$	(5.73 ±0.27) × 10^{-5}

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 16 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 8.7 for 13 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|ccc}
x_3 & -64 & & \\
x_4 & -77 & 0 & \\
x_5 & -5 & 0 & 0 \\
\hline
 & x_1 & x_3 & x_4
\end{array}$$

Σ^- BRANCHING RATIOS

$\Gamma(n\pi^-\gamma)/\Gamma(n\pi^-)$ Γ_2/Γ_1

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value for the Summary Table.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.46±0.06	292	EBENHOH	73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.10±0.02	23	ANG	69B	HBC	$\pi^- < 110$ MeV/c
~ 1.1		BAZIN	65B	HBC	$\pi^- < 166$ MeV/c

$\Gamma(n e^- \overline{\nu}_e)/\Gamma(n\pi^-)$ Γ_3/Γ_1

Measurements with an error $\geq 0.2 \times 10^{-3}$ have been omitted.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.019±0.034 OUR FIT					
$1.019^{+0.031}_{-0.036}$ OUR AVERAGE					
0.96 ±0.05	2847	BOURQUIN	83C	SPEC	SPS hyperon beam
$1.09\ ^{+0.06}_{-0.08}$	601	[3] EBENHOH	74	HBC	$K^- p$ at rest
$1.05\ ^{+0.07}_{-0.13}$	455	[3] SECHI-ZORN	73	HBC	$K^- p$ at rest
0.97 ±0.15	57	COLE	71	HBC	$K^- p$ at rest
1.11 ±0.09	180	BIERMAN	68	HBC	

[3] An additional negative systematic error is included for internal radiative corrections and latest form factors; see BOURQUIN 83C.

$\Gamma(n \mu^- \overline{\nu}_\mu)/\Gamma(n\pi^-)$ Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.45±0.04 OUR FIT					
0.45±0.04 OUR AVERAGE					
0.38±0.11	13	COLE	71	HBC	$K^- p$ at rest
0.43±0.06	72	ANG	69	HBC	$K^- p$ at rest
0.43±0.09	56	BAGGETT	69	HBC	$K^- p$ at rest
0.56±0.20	11	BAZIN	65B	HBC	$K^- p$ at rest
0.66±0.15	22	COURANT	64	HBC	

$\Gamma(\Lambda e^- \overline{\nu}_e)/\Gamma(n\pi^-)$ Γ_5/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.574±0.027 OUR FIT					
0.574±0.027 OUR AVERAGE					
0.561±0.031	1620	[4] BOURQUIN	82	SPEC	SPS hyperon beam
0.63 ±0.11	114	THOMPSON	80	ASPK	Hyperon beam
0.52 ±0.09	31	BALTAY	69	HBC	$K^- p$ at rest
0.69 ±0.12	31	EISELE	69	HBC	$K^- p$ at rest
0.64 ±0.12	35	BARASH	67	HBC	$K^- p$ at rest
0.75 ±0.28	11	COURANT	64	HBC	$K^- p$ at rest

[4] The value is from BOURQUIN 83B, and includes radiation corrections and new acceptance.

Σ^- DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. Older, outdated results have been omitted.

α_- FOR $\Sigma^- \rightarrow n\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.068±0.008 OUR AVERAGE					
−0.062±0.024	28k	HANSL	78	HBC	$K^- p \rightarrow \Sigma^- \pi^+$
−0.067±0.011	60k	BOGERT	70	HBC	$K^- p$ 0.4 GeV/c
−0.071±0.012	51k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

ϕ ANGLE FOR $\Sigma^- \rightarrow n\pi^-$ $(\tan\phi = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
10±15 OUR AVERAGE					
+ 5±23	1092	[5] BERLEY	70B	HBC	n rescattering
14±19	1385	BANGERTER	69B	HBC	$K^- p$ 0.4 GeV/c

[5] BERLEY 70B changed from −5 to +5° to agree with our sign convention.

g_A/g_V FOR $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the "Note on Baryon Decay Parameters" in the neutron Listings. What is actually listed is $|g_1/f_1 - 0.237 g_2/f_1|$. This reduces to $g_A/g_V \equiv g_1(0)/f_1(0)$ on making the usual assumption that $g_2 = 0$. See also the note on HSUEH 88.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.340±0.017 OUR AVERAGE					
+0.327±0.007±0.019	50k	[6] HSUEH	88	SPEC	Σ^- 250 GeV
+0.34 ±0.05	4456	[7] BOURQUIN	83C	SPEC	SPS hyperon beam
0.385±0.037	3507	[8] TANENBAUM	74	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.29 ±0.07	25k	HSUEH	85	SPEC	See HSUEH 88
$0.17\ ^{+0.07}_{-0.09}$	519	DECAMP	77	ELEC	Hyperon beam

[6] The sign is, *with our conventions*, unambiguously positive. The value assumes, as usual, that $g_2 = 0$. If g_2 is included in the fit, than (with our sign convention) $g_2 = -0.56 \pm 0.37$, with a corresponding reduction of g_A/g_V to $+0.20 \pm 0.08$.

[7] BOURQUIN 83C favors the positive sign by at least 2.6 standard deviations.

[8] TANENBAUM 74 gives 0.435 ± 0.035, assuming no q^2 dependence in g_A and g_V. The listed result allows q^2 dependence, and is taken from HSUEH 88.

$f_2(0)/f_1(0)$ FOR $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

The signs have been changed to be in accord with our conventions, given in the "Note on Baryon Decay Parameters" in the neutron Listings.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.97±0.14 OUR AVERAGE					
+0.96±0.07±0.13	50k	HSUEH	88	SPEC	Σ^- 250 GeV
+1.02±0.34	4456	BOURQUIN	83C	SPEC	SPS hyperon beam

TRIPLE CORRELATION COEFFICIENT D for $\Sigma^- \rightarrow n e^- \overline{\nu}_e$

The coefficient D of the term $D\, \mathbf{P}\cdot(\mathbf{p}_e \times \mathbf{p}_\nu)$ in the $\Sigma^- \rightarrow n e^- \overline{\nu}$ decay angular distribution. A nonzero value would indicate a violation of time-reversal invariance.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.11±0.10	50k	HSUEH	88	SPEC	Σ^- 250 GeV

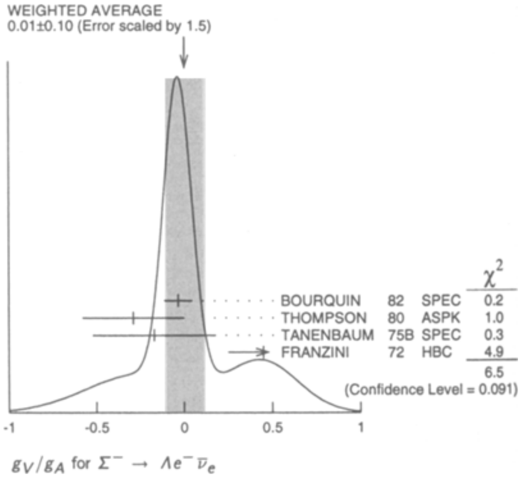
g_V/g_A FOR $\Sigma^- \rightarrow \Lambda e^- \overline{\nu}_e$

For the sign convention, see the "Note on Baryon Decay Parameters" in the neutron Listings. The value is predicted to be zero by conserved vector current theory. The values averaged assume CVC-SU(3) weak magnetism term.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.01 ±0.10 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.			
−0.034±0.080	1620	[9] BOURQUIN	82	SPEC	SPS hyperon beam
−0.29 ±0.29	114	THOMPSON	80	ASPK	BNL hyperon beam
−0.17 ±0.35	55	TANENBAUM	75B	SPEC	BNL hyperon beam
+0.45 ±0.20	186	[9,10] FRANZINI	72	HBC	

[9] The sign has been changed to agree with our convention.

[10] The FRANZINI 72 value includes the events of earlier papers.



g_{WM}/g_A FOR $\Sigma^- \rightarrow \Lambda e^- \overline{\nu}_e$

The values quoted assume the CVC prediction $g_V = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.4 ±1.7 OUR AVERAGE					
1.75±3.5	114	THOMPSON	80	ASPK	BNL hyperon beam
3.5 ±4.5	55	TANENBAUM	75B	SPEC	BNL hyperon beam
2.4 ±2.1	186	FRANZINI	72	HBC	

Σ^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

GUREV	93	JETPL 57 400 Translated from ZETFP 57 389.	Gur'ev, Denisov, Zhelamkov, Ivanov+	(PNPI)
GALL	88	PRL 60 186	+Austin+	(BOST, MIT, WILL, CIT, CMU, WYOM)
HERTZOG	88	PR D37 1142	+Eckhause+	(WILL, BOST, MIT, CIT, CMU, WYOM)
HSUEH	88	PR D38 2056	+	(CHIC, ELMT, FNAL, IOWA, ISU, PNPI, YALE)
ZAPALAC	86	PRL 57 1526	+	(EFI, ELMT, FNAL, IOWA, ISU, PNPI, YALE)
HSUEH	85	PRL 54 2399	+Muller+	(CHIC, ELMT, FNAL, ISU, PNPI, YALE)
WAH	85	PRL 55 2551	+Cardello, Cooper, Teig+	(FNAL, IOWA, ISU)
BOURQUIN	83B	ZPHY C21 27	+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
BOURQUIN	83C	ZPHY C21 17	+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
DECK	83	PR D28 1	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
BOURQUIN	82	ZPHY C12 307	+Brown+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
HANSL	78	NP B132 45	+Manz, Matt, Reucroft, Settles+	(MPIM, VAND)
DECAMP	77	PL 66B 295	+Badier, Bland, Chollet, Gaillard+	(LALO, EPOL)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
DUGAN	75	NP A254 396	+Asano, Chen, Cheng, Hu, Lidofsky+	(COLU, YALE)
TANENBAUM	75B	PR D12 1871	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEIDT)
TANENBAUM	74	PRL 33 175	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEIDT)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BOHM	72	NP B48 1	+	(BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
FRANZINI	72	PR D6 2417	+	(COLU, HEID, UMD, STON)
ROBERTSON	72	Thesis UMI 78-00877		(IIT)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
Also	69	Thesis Nevis 175	Norton	(COLU)
TOVEE	71	NP B33 493	+	(LOUC, KIDR, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)

BOGERT	70	PR D2 6	+Lucas, Taft, Willis, Berley+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
PDG	70	RMP 42 No. 1	Barbaro-Galtieri, Derenzo, Price+	(LRL, BRAN, CERN+)
ANG	69	ZPHY 223 103	+Eisele, Engelmann, Filthuth+	(HEID)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69	PRL 23 249	+Kehoe, Snow	(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	Thesis UCRL 19244		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
BIERMAN	68	PRL 20 1459	+Kounosu, Nauenberg+	(PRIN)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
WHITESIDE	68	NC 54A 537	+Gollub	(OBER)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
CHANG	66	PR 151 1081		(COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
Also	66	PR 151 1081	Chang	(COLU)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\Sigma(1385)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗∗∗

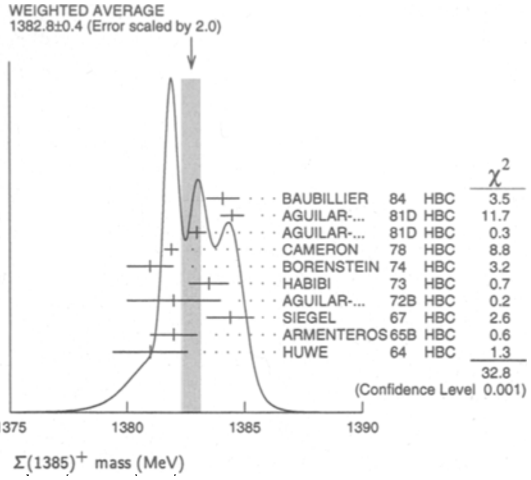
Discovered by ALSTON 60. Early measurements of the mass and width for combined charge states have been omitted. They may be found in our 1984 edition Reviews of Modern Physics **56** No. 2 Pt. II (1984).

We average only the most significant determinations. We do not average results from inclusive experiments with large backgrounds or results which are not accompanied by some discussion of experimental resolution. Nevertheless systematic differences between experiments remain. (See the ideograms in the Listings below.) These differences could arise from interference effects that change with production mechanism and/or beam momentum. They can also be accounted for in part by differences in the parametrizations employed. (See BORENSTEIN 74 for a discussion on this point.) Thus BORENSTEIN 74 uses a Breit-Wigner with energy-independent width, since a *P*-wave was found to give unsatisfactory fits. CAMERON 78 uses the same form. On the other hand HOLMGREN 77 obtains a good fit to their $\Lambda\pi$ spectrum with a *P*-wave Breit-Wigner, but includes the partial width for the $\Sigma\pi$ decay mode in the parametrization. AGUILAR-BENITEZ 81D gives masses and widths for five different Breit-Wigner shapes. The results vary considerably. Only the best-fit *S*-wave results are given here.

$\Sigma(1385)$ MASSES

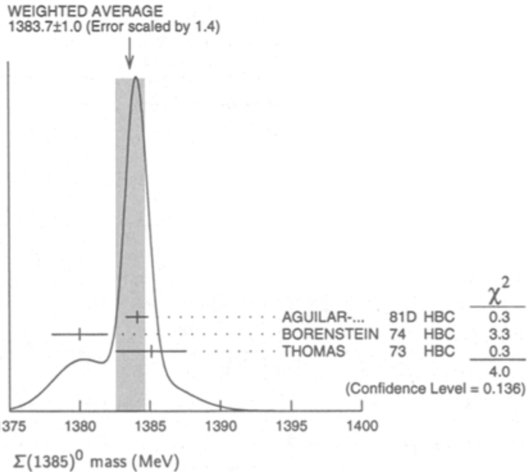
$\Sigma(1385)^+$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1382.8±0.4	**OUR AVERAGE**	Error includes scale factor of 2.0. See the ideogram below.		
1384.1±0.7	1897	BAUBILLIER 84	HBC	$K^- p$ 8.25 GeV/c
1384.5±0.5	5256	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1383.0±0.4	9361	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1381.9±0.3	6900	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
1381 ±1	6846	BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
1383.5±0.85	2300	HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
1382 ±2	400	AGUILAR-... 72B	HBC	$K^- p \to \Lambda\pi$'s
1384.4±1.0	1260	SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
1382 ±1	750	ARMENTEROS 65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1381.0±1.6	859	HUWE 64	HBC	$K^- p$ 1.22 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1385.1±1.2	600	BAKER 80	HYBR	$\pi^+ p$ 7 GeV/c
1383.2±1.0	750	BAKER 80	HYBR	$K^- p$ 7 GeV/c
1381 ±2	7k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
1391 ±2	2k	CAUTIS 79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
1390 ±2	100	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
1385 ±3	22k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
1385 ±1	2594	HOLMGREN 77	HBC	See AGUILAR 81D
1380 ±2		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
1382 ±1	3740	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
1390 ±6	46	AGUILAR-... 70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
1383 ±8	62	[4] BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
1378 ±5	135	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
1384.3±1.9	250	[4] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
1382.6±2.1	250	[4] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
1375.0±3.9	170	COOPER 64	HBC	$K^- p$ 1.45 GeV/c
1376.0±3.9	154	[4] ELY 61	HLBC	$K^- p$ 1.11 GeV/c



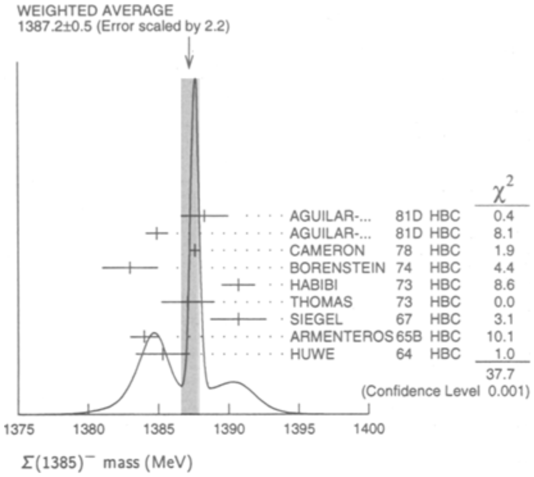
$\Sigma(1385)^0$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1383.7±1.0	**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram below.		
1384.1±0.8	5722	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1380 ±2	3100	[5] BORENSTEIN 74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
1385.1±2.5	240	[4] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1389 ±3	500	[6] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c



$\Sigma(1385)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1387.2±0.5	**OUR AVERAGE**	Error includes scale factor of 2.2. See the ideogram below.		
1388.3±1.7	620	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1384.9±0.8	3346	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1387.6±0.3	9720	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
1383 ±2	2303	BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
1390.7±1.2	1900	HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
1387.1±1.9	630	[4] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^- K^+$
1390.7±2.0	370	SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
1384 ±1	1380	ARMENTEROS 65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1385.3±1.9	1086	[4] HUWE 64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1383 ±1	4.5k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
1380 ±6	150	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
1387 ±3	12k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
1391 ±3	193	HOLMGREN 77	HBC	See AGUILAR 81D
1383 ±2		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
1389 ±1	3060	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
1389 ±9	15	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
1391.5±2.6	120	[4] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
1399.8±2.2	58	[4] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
1392.0±6.2	200	COOPER 64	HBC	$K^- p$ 1.45 GeV/c
1382 ±3	93	DAHL 61	DBC	$K^- d$ 0.45 GeV/c
1376.0±4.4	224	[4] ELY 61	HLBC	$K^- p$ 1.11 GeV/c



Σ(1385)$^-$ mass (MeV)

$m_{\Sigma(1385)^-} - m_{\Sigma(1385)^+}$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−2 to +6	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
7.2±1.4		[7] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
6.3±2.0		[7] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
11 ±9		[7] LONDON	66	HBC	$K^- p$ 2.24 GeV/c
9 ±6		LONDON	66	HBC	$\Lambda 3\pi$ events
2.0±1.5		[7] ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
7.2±2.1		[7] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
17.2±2.0		[7] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
17 ±7		[7] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
4.3±2.2		[7] HUWE	64	HBC	$K^- p$ 1.22 GeV/c
0.0±4.2		[7] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

$m_{\Sigma(1385)^0} - m_{\Sigma(1385)^+}$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−4 to +4	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c

$m_{\Sigma(1385)^-} - m_{\Sigma(1385)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0±2.4	[7] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^+$

Σ(1385) WIDTHS

Σ(1385)$^+$ WIDTH

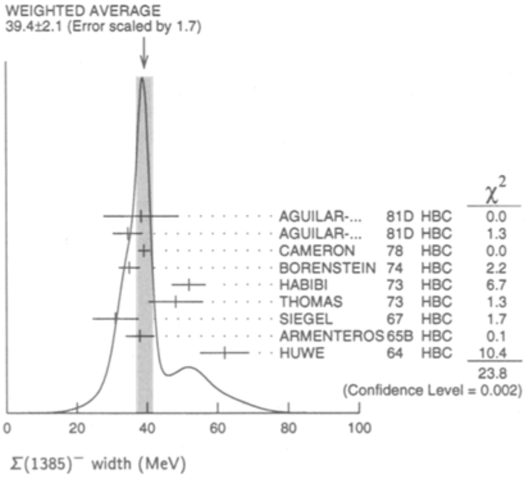
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35.8± 0.8 OUR AVERAGE					
37.2± 2.0	1897	BAUBILLIER	84	HBC	$K^- p$ 8.25 GeV/c
35.1± 1.7	5256	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
37.5± 2.0	9361	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
35.5± 1.9	6900	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
34.0± 1.6	6846	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
38.3± 3.2	2300	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
32.5± 6.0	400	AGUILAR-...	72B	HBC	$K^- p \to \Lambda\pi$'s
36 ± 4	1260	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
32.0± 4.7	750	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
46.5± 6.4	859	[9] HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
40 ± 3	600	BAKER	80	HYBR	$\pi^+ p$ 7 GeV/c
37 ± 2	750	BAKER	80	HYBR	$K^- p$ 7 GeV/c
37 ± 2	7k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
30 ± 4	2k	CAUTIS	79	HYBR	$\pi^+ p / K^- p$ 11.5 GeV
30 ± 6	100	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
43 ± 5	22k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
34 ± 2	2594	HOLMGREN	77	HBC	See AGUILAR 81D
40.0± 3.2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
48 ± 3	3740	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
33 ±20	46	[9] AGUILAR-...	70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
25 ±32	62	[9] BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
30.3± 7.5	250	[9] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
33.1± 8.3	250	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
51 ±16	170	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
48 ±16	154	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

Σ(1385)^0 WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
36 ± 5 OUR AVERAGE					
34.8± 5.6	5722	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.3±10.2	240	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
53 ± 8	3100	[10] BORENSTEIN	74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
30 ± 9	106	CURTIS	63	OSPK	$\pi^- p$ 1.5 GeV/c

Σ(1385)$^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
39.4± 2.1 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.					
38.4±10.7	620	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
34.6± 4.2	3346	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.2± 1.7	9720	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
35 ± 3	2303	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
51.9± 4.8	1900	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
48.2± 7.7	630	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^0$
31.0± 6.5	370	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
38.0± 4.1	1382	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
62 ± 7	1086	HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
44 ± 4	4.5k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
58 ± 4	150	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
45 ± 5	12k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
35 ±10	193	HOLMGREN	77	HBC	See AGUILAR 81D
47 ± 6		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
40 ± 3	3060	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
29.2±10.6	120	[9] SMITH	65	HBC	$K^- p$ 1.80 GeV/c
17.1± 8.9	58	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
88 ±24	200	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
40		DAHL	61	DBC	$K^- d$ 0.45 GeV/c
66 ±18	224	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c



Σ(1385)$^-$ width (MeV)

Σ(1385) POLE POSITIONS

Σ(1385)$^+$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1379±1	LICHTENBERG74	Extrapolates HABIBI 73

Σ(1385)$^+$ −IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
17.5±1.5	LICHTENBERG74	Extrapolates HABIBI 73

Σ(1385)$^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1383±1	LICHTENBERG74	Extrapolates HABIBI 73

Σ(1385)$^-$ −IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
22.5±1.5	LICHTENBERG74	Extrapolates HABIBI 73

Σ(1385) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	88±2 %
Γ_2	$\Sigma\pi$	12±2 %
Γ_3	$\Lambda\gamma$	
Γ_4	$\Sigma\gamma$	
Γ_5	$N\overline{K}$	

The above branching fractions are our estimates, not fits or averages.

Σ(1385) BRANCHING RATIOS

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.135±0.011 OUR AVERAGE					
0.20 ±0.06	DIONISI	78B	HBC	±	$K^- p \rightarrow Y^* K \overline{K}$
0.16 ±0.03	BERTHON	74	HBC	+	$K^- p$ 1.26–1.84 GeV/c
0.11 ±0.02	BERTHON	74	HBC	−	$K^- p$ 1.26–1.84 GeV/c
0.21 ±0.05	BORENSTEIN	74	HBC	+	$K^- p \rightarrow \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.18 ±0.04	MAST	73	MPWA	±	$K^- p \rightarrow \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.10 ±0.05	THOMAS	73	HBC	−	$\pi^- p \rightarrow \Lambda K\pi$, $\Sigma K\pi$
0.16 ±0.07	AGUILAR-...	72B	HBC	+	$K^- p$ 3.9, 4.6 GeV/c
0.13 ±0.04	COLLEY	71B	DBC	−0	$K^- N$ 1.5 GeV/c
0.13 ±0.04	PAN	69	HBC	+	$\pi^+ p \rightarrow \Lambda K\pi$, $\Sigma K\pi$
0.08 ±0.06	LONDON	66	HBC	+	$K^- p$ 2.24 GeV/c
0.163±0.041	ARMENTEROS	65B	HBC	±	$K^- p$ 0.95–1.20 GeV/c
0.09 ±0.04	HUWE	64	HBC	±	$K^- p$ 1.2–1.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	ALSTON	62	HBC	±0	$K^- p$ 1.15 GeV/c
0.04 ±0.04	BASTIEN	61	HBC	±	

$\Gamma(\Lambda\gamma)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.17±0.17	1	MEISNER	72	HBC	1 event only

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$\Gamma(\Sigma\gamma)/\Gamma(\Lambda\pi)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1385) \rightarrow \Lambda\pi$ $(\Gamma_5\Gamma_1)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		CHG	COMMENT
+0.586±0.319	[11] DEVENISH	74B	0	Fixed-t dispersion rel.

Σ(1385) FOOTNOTES

[1] From fit to inclusive $\Lambda\pi$ spectrum.
[2] Includes data of HOLMGREN 77.
[3] The errors are statistical only. The resolution is not unfolded.
[4] The error is enlarged to $\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[5] From a fit to $\Lambda\pi^0$ with the width fixed at 34 MeV.
[6] From fit to inclusive $\Lambda\pi^0$ spectrum with the width fixed at 40 MeV.
[7] Redundant with data in the mass Listings.
[8] Results from $\Lambda\pi^+\pi^-$ and $\Lambda\pi^+\pi^-\pi^0$ combined by us.
[9] The error is enlarged to $4\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[10] Consistent with +, 0, and − widths equal.
[11] An extrapolation of the parametrized amplitude below threshold.

Σ(1385) REFERENCES

BAUBILLIER 84 ZPHY C23 213 + (BIRM, CERN, GLAS, MSU, CURIN)
PDG 84 RMP 56 No. 2 Pt. II Wohl, Cahn, Rittenberg+ (LBL, CIT, CERN)
AGUILAR-... 81D AFIS A77 144 Aguilar-Benitez, Salicio (MADR)
BAKER 80 NP B166 207 +Chima, Dornan, Gibbs, Hall, Miller+ (LOIC)
BAUBILLIER 79B NP B148 18 + (BIRM, CERN, GLAS, MSU, CURIN)
CAUTIS 79 NP B156 507 +Ballam, Bouchez, Carroll, Chadwick+ (SLAC)
SUGAHARA 79B NP B156 237 +Ochiai, Fukui, Cooper+ (KEK, OSKC, KINK)
CAMERON 78 NP B143 189 +Franek, Gopal, Bacon, Butterworth+ (RHEL, LOIC)
DIONISI 78B PL 78B 154 +Armenteros, Diaz (CERN, AMST, NIJM, OXF)
BARREIRO 77B NP B126 319 +Berge, Ganguli, Blokzijl+ (CERN, AMST, NIJM)
HOLMGREN 77 NP B119 261 +Aguilar-Benitez, Kluyver+ (CERN, AMST, NIJM)
BARDADIN-... 75 NP B98 418 Bardadin-Otwinowska+ (SACL, EPOL, RHEL)
COLAS 75 NP B91 253 +Farwell, Ferrer, Six (ORSAY)
BERTHON 74 NC 21A 146 +Tristram+ (CDEF, RHEL, SACL, STRB)
BORENSTEIN 74 PR D9 3006 +Kalbfleisch, Strand+ (BNL, MICH)
DEVENISH 74B NP B81 330 +Froggatt, Martin (DESY, NORD, LOUC)
LICHTENBERG 74 PR D10 3865 (IND)
Also 74B Private Comm. Lichtenberg (IND)
HABIBI 73 Thesis Nevis 199 (COLU)
Also 73 Purdue Conf. 387 Baltay, Bridgewater, Cooper+ (COLU, BING)
MAST 73 PR D7 3212 +Bangerter, Alston-Garnjost+ (LBL) IJP
Also 73B PR D7 5 Mast, Bangerter, Alston-Garnjost+ (LBL) IJP
THOMAS 73 NP B56 15 +Engler, Fisk, Kraemer (CMU) JP
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
MEISNER 72 NC 12A 62 (UNC, LBL)
COLLEY 71B NP B31 61 +Cox, Eastwood, Fry+ (BIRM, EDIN, GLAS, LOIC)
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
PAN 69 PRL 23 808 +Forman (PENN) I
SIEGEL 67 Thesis UCRL 18041 (LRL)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) J
ARMENTEROS 65B PL 19 75 + (CERN, HEID, SACL)
SMITH 65 Thesis UCLA (UCLA)
COOPER 64 PL 8 365 +Filthuth, Fridman, Malamud+ (CERN, AMST)
HUWE 64 Thesis UCRL 11291 (LRL) JP
Also 69 PR 180 1824 Huwe (LRL)
CURTIS 63 PR 132 1771 +Coffin, Meyer, Terwilliger (MICH) J
ALSTON 62 CERN Conf. 311 +Alvarez, Ferro-Luzzi+ (LRL)
BASTIEN 61 PRL 6 702 +Ferro-Luzzi, Rosenfeld (LRL)
DAHL 61 PRL 6 142 +Horwitz, Miller, Murray, White (LRL)
ELY 61 PRL 7 461 +Fung, Gidal, Pan, Powell, White (LRL) J
ALSTON 60 PRL 5 520 +Alvarez, Eberhard, Good, Graziano+ (LRL) I

Σ(1480) Bumps

$I(J^P) = 1(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

These are peaks seen in $\Lambda\pi$ and $\Sigma\pi$ spectra in the reaction $\pi^+ p \rightarrow (Y\pi)K^+$ at 1.7 GeV/c. Also, the Y polarization oscillates in the same region.

MILLER 70 suggests a possible alternate explanation in terms of a reflection of $N(1675) \rightarrow \Lambda K$ decay. However, such an explanation for the $(\Sigma^+\pi^0)K^+$ channel in terms of $\Delta(1650) \rightarrow \Sigma K$ decay seems unlikely (see PAN 70). In addition such reflections would also have to account for the oscillation of the Y polarization in the 1480 MeV region.

HANSON 71, with less data than PAN 70, can neither confirm nor deny the existence of this state. MAST 75 sees no structure in this region in $K^- p \rightarrow \Lambda\pi^0$.

ENGELEN 80 performs a multichannel analysis of $K^- p \rightarrow p\overline{K}^0\pi^-$ at 4.2 GeV/c. They observe a 3.5 standard-deviation signal at 1480 MeV in $p\overline{K}^0$ which cannot be explained as a reflection of any competing channel.

Σ(1480) MASS
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1480 OUR ESTIMATE						
1480	120	ENGELEN	80	HBC	+	$K^- p \rightarrow (p\overline{K}^0)\pi^-$
1485±10		CLINE	73	MPWA	−	$K^- d \rightarrow (\Lambda\pi^-)p$
1479±10		PAN	70	HBC	+	$\pi^+ p \rightarrow (\Lambda\pi^+)K^+$
1465±15		PAN	70	HBC	+	$\pi^+ p \rightarrow (\Sigma\pi)K^+$

Σ(1480) WIDTH
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
80±20	120	ENGELEN	80	HBC	+	$K^- p \rightarrow (p\overline{K}^0)\pi^-$
40±20		CLINE	73	MPWA	−	$K^- d \rightarrow (\Lambda\pi^-)p$
31±15		PAN	70	HBC	+	$\pi^+ p \rightarrow (\Lambda\pi^+)K^+$
30±20		PAN	70	HBC	+	$\pi^+ p \rightarrow (\Sigma\pi)K^+$

$\Sigma(1480)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1480)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	CHG
0.82±0.51	PAN 70	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	CHG
0.72±0.50	PAN 70	HBC	+

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
small	CLINE 73	MPWA	$K^- d \to (\Lambda\pi^-)p$

$\Sigma(1480)$ REFERENCES (PRODUCTION EXPERIMENTS)

ENGELEN	80	NP B167 61	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
MAST	75	PR D11 3078	+Alston-Garnjost, Bangerter+	(LBL)
CLINE	73	LNC 6 205	+Laumann, Mapp	(WISC) IJP
HANSON	71	PR D4 1296	+Kalmus, Louie	(LBL) I
MILLER	70	Duke Conf. 229		(PURD)
PAN	70	PR D2 49	+Forman, Ko, Hagopian, Selove	(PENN)
Also	69	PRL 23 808	Pan, Forman	(PENN) I
Also	69B	PRL 23 806	Pan, Forman	(PENN) I

$\Sigma(1560)$ Bumps

$I(J^P) = 1(?^?)$ Status: **

OMITTED FROM SUMMARY TABLE

This entry lists peaks reported in mass spectra around 1560 MeV without implying that they are necessarily related.

DIONISI 78B observes a 6 standard-deviation enhancement at 1553 MeV in the charged $\Lambda/\Sigma\pi$ mass spectra from $K^- p \to (\Lambda/\Sigma)\pi K\overline{K}$ at 4.2 GeV/c. In a CERN ISR experiment, LOCKMAN 78 reports a narrow 6 standard-deviation enhancement at 1572 MeV in $\Lambda\pi^{\pm}$ from the reaction $pp \to \Lambda\pi^+\pi^- X$. These enhancements are unlikely to be associated with the $\Sigma(1580)$ (which has not been confirmed by several recent experiments – see the next entry in the Listings).

CARROLL 76 observes a bump at 1550 MeV (as well as one at 1580 MeV) in the isospin-1 $\overline{K}N$ total cross section, but uncertainties in cross section measurements outside the mass range of the experiment preclude estimating its significance.

See also MEADOWS 80 for a review of this state.

$\Sigma(1560)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
≈ 1560 OUR ESTIMATE					
1553±7	121	DIONISI 78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
1572±4	40	LOCKMAN 78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
79±30	121	DIONISI 78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
15± 6	40	[1] LOCKMAN 78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	seen
Γ_2	$\Sigma\pi$	

$\Sigma(1560)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.35±0.12	DIONISI 78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$

$\Gamma(\Lambda\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	LOCKMAN 78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] The width observed by LOCKMAN 78 is consistent with experimental resolution.

$\Sigma(1560)$ REFERENCES (PRODUCTION EXPERIMENTS)

MEADOWS	80	Toronto Conf. 283		(CINC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF) I
LOCKMAN	78	Saclay DPHPE 78-01	+Meyer, Rander, Poster, Schlein+	(UCLA, SACL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I

$\Sigma(1580)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

Seen in the isospin-1 $\overline{K}N$ cross section at BNL (LI 73, CARROLL 76) and in a partial-wave analysis of $K^- p \to \Lambda\pi^0$ for c.m. energies 1560–1600 MeV by LITCHFIELD 74. LITCHFIELD 74 finds $J^P = 3/2^-$. Not seen by ENGLER 78 or by CAMERON 78C (with larger statistics in $K^0_L p \to \Lambda\pi^+$ and $\Sigma^0\pi^+$).

$\Sigma(1580)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 1580 OUR ESTIMATE			
1583±4	[1] CARROLL 76	DPWA	Isospin-1 total σ
1582±4	[2] LITCHFIELD 74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
15	[1] CARROLL 76	DPWA	Isospin-1 total σ
11±4	[2] LITCHFIELD 74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1580)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
+0.03±0.01	[2] LITCHFIELD 74	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1580) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	CAMERON 78C	HBC	$K^0_L p \to \Lambda\pi^+$
not seen	ENGLER 78	HBC	$K^0_L p \to \Lambda\pi^+$
+0.10±0.02	[2] LITCHFIELD 74	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1580) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	CAMERON 78C	HBC	$K^0_L p \to \Sigma^0\pi^+$
not seen	ENGLER 78	HBC	$K^0_L p \to \Sigma^0\pi^+$
+0.03±0.04	[2] LITCHFIELD 74	DPWA	$\overline{K}N$ multichannel

$\Sigma(1580)$ FOOTNOTES

[1] CARROLL 76 sees a total-cross-section bump with $(J+1/2)\ \Gamma_{\text{el}} / \Gamma_{\text{total}} = 0.06$.

[2] The main effect observed by LITCHFIELD 74 is in the $\Lambda\pi$ final state; the $\overline{K}N$ and $\Sigma\pi$ couplings are estimated from a multichannel fit including total-cross-section data of LI 73.

Σ(1580) REFERENCES

CAMERON	78C	NP B132 189	+Capiluppi+	(BGNA, EDIN, GLAS, PISA, RHEL) I
ENGLER	78	PR D18 3061	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
LITCHFIELD	74	PL 51B 509		(CERN) IJP
LI	73	Purdue Conf. 283		(BNL) I

Σ(1620) S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The S_{11} state at 1697 MeV reported by VANHORN 75 is tentatively listed under the Σ(1750). CARROLL 76 sees two bumps in the isospin-1 total cross section near this mass.

Production experiments are listed separately in the next entry.

Σ(1620) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1620 OUR ESTIMATE				
1600± 6	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
1608± 5	[2] CARROLL	76	DPWA	Isospin-1 total σ
1633±10	[3] CARROLL	76	DPWA	Isospin-1 total σ
1630±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
1620	KIM	71	DPWA	K-matrix analysis

Σ(1620) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
87±19	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
15	[2] CARROLL	76	DPWA	Isospin-1 total σ
10	[3] CARROLL	76	DPWA	Isospin-1 total σ
65±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis

Σ(1620) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1620) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.05	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1620) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.02	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
0.15	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1620) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
0.40±0.06	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.08	KIM	71	DPWA	K-matrix analysis

Σ(1620) FOOTNOTES

[1] MORRIS 78 obtains an equally good fit without including this resonance.

[2] Total cross-section bump with $(J+1/2)\ \Gamma_{el} / \Gamma_{total}$ is 0.06 seen by CARROLL 76.

[3] Total cross-section bump with $(J+1/2)\ \Gamma_{el} / \Gamma_{total}$ is 0.04 seen by CARROLL 76.

Σ(1620) REFERENCES

MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP

Σ(1620) Production Experiments

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the previous entry.

The results of CRENNELL 69B at 3.9 GeV/c are not confirmed by SABRE 70 at 3.0 GeV/c. However, at 4.5 GeV/c, AMMANN 70 sees a peak at 1642 MeV which on the basis of branching ratios they do not associate with the Σ(1670). See MILLER 70 for a review of these conflicts.

Σ(1620) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1620 OUR ESTIMATE						
1642±12		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
1618± 3	20	BLUMENFELD	69	HBC	+	$K^0_L p$
1619± 8		CRENNELL	69B	DBC	±	$K^- N \to \Lambda\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1616± 8		CRENNELL	68	DBC	±	See CRENNELL 69B

Σ(1620) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
55±24		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
30±10	20	BLUMENFELD	69	HBC	+	
72^{+22}_{-15}		CRENNELL	69B	DBC	±	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
66±16		CRENNELL	68	DBC	±	See CRENNELL 69B

Σ(1620) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma(1385)\pi$
Γ_6	$\Lambda(1405)\pi$

Σ(1620) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda\pi\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG
∼ 2.5	14	BLUMENFELD	69	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.4±0.4	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.0±0.1	CRENNELL	68	DBC	+	See CRENNELL 69B

$\Gamma(\Lambda\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG
large	CRENNELL	68	DBC	±

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.3	95	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.2±0.1		CRENNELL	68	DBC	±	

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	95	AMMANN	70	DBC	$K^- N$ 4.5 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Lambda\pi)$ Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.7±0.4	AMMANN	70	DBC	$K^- p$ 4.5 GeV/c

Σ(1620) REFERENCES (PRODUCTION EXPERIMENTS)

AMMANN 70 PRL 24 327 +Garfinkel, Carmony, Gutay+ (PURD, IND)
Also 73 PR D7 1345 Ammann, Carmony, Garfinkel+ (PURD, IUPU)
MILLER 70 Duke Conf. 229 (PURD)
SABRE 70 NP B16 201 Barloutaud, Merril, Schever+ (SABRE Collab.)
BLUMENFELD 69 PL 29B 58 +Kalbfleisch (BNL) I
CRENNELL 69B Lund Paper 183 +Karshon, Lai, O'Neil, Scarr+ (BNL, CUNY) I
Results are quoted in LEVI-SETTI 69C.
Also 69C Lund Conf. Levi-Setti (EFI)
CRENNELL 68 PRL 21 648 +Delaney, Flaminio, Karshon+ (BNL, CUNY) I

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Σ(1660) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1690 (≈ 1660) OUR ESTIMATE				
1665.1±11.2	[1] KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
1670 ±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1679 ±10	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1676 ±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1668 ±25	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
1670 ±20	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1565 or 1597	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1660 ±30	[3] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
1671 ± 2	[4] PONTE	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$

Σ(1660) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 200 (≈ 100) OUR ESTIMATE				
81.5± 22.2	[1] KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
152 ± 20	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
38 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
120 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
230^{+165}_{-60}	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
250 ±110	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
202 or 217	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80 ± 40	[3] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
81 ± 10	[4] PONTE	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$

Σ(1660) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–30 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen

Σ(1660) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.12±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.10±0.05	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.04	GOPAL	77	DPWA	See GOPAL 80
0.27 or 0.29	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Sigma(1660) \rightarrow \Lambda\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$0.12^{+0.12}_{-0.04}$	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.11	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.04±0.02	[3] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
+0.16±0.01	[4] PONTE	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Sigma(1660) \rightarrow \Sigma\pi$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13±0.04	[1] KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
−0.16±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.11±0.01	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34 or −0.37	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^- N \rightarrow \Sigma\pi$

Σ(1660) FOOTNOTES

[1] The evidence of KOISO 85 is weak.
[2] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[3] From solution 1 of BAILLON 75; not present in solution 2.
[4] From solution 2 of PONTE 75; not present in solution 1.

Σ(1660) REFERENCES

KOISO 85 NP A433 619 +Sai, Yamamoto, Kofler (TOKY, MASA)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEIDH, MPIM) IJP
BAILLON 75 NP B94 39 +Litchfield (CERN, RHEL) IJP
PONTE 75 PR D12 2597 +Hertzbach, Button-Shafer+ (MASA, TENN, UCR) IJP
VANHORN 75 NP B87 145 (LBL) IJP
Also 75B NP B87 157 VanHorn (LBL) IJP
KANE 74 LBL-2452 (LBL) IJP

THE Σ(1670) REGION

Production experiments: The measured $\Sigma\pi/\Sigma\pi\pi$ branching ratio for the $\Sigma(1670)$ produced in the reaction $K^- p \rightarrow \pi^-\Sigma(1670)^+$ is strongly dependent on momentum transfer. This was first discovered by EBERHARD 69, who suggested that there exist two Σ resonances with the same mass and quantum numbers: one with a large $\Sigma\pi\pi$ (mainly $\Lambda(1405)\pi$) branching fraction produced peripherally, and the other with a large $\Sigma\pi$ branching fraction produced at larger angles. The experimental results have been confirmed by AGUILAR-BENITEZ 70, ASPELL 74, ESTES 74, and TIMMERMANS 76. If, in fact, there are two resonances, the most likely quantum numbers for both the $\Sigma\pi$ and the $\Lambda(1405)\pi$ states are D_{13}. There is also possibly a third Σ in this region, the $\Sigma(1690)$ in the Listings, the main evidence for which is a large $\Lambda\pi/\Sigma\pi$ branching ratio. These topics have been reviewed by EBERHARD 73 and by MILLER 70.

Formation experiments: Two states are also observed near this mass in formation experiments. One of these, the $\Sigma(1670)D_{13}$, has the same quantum numbers as those observed in production and has a large $\Sigma\pi/\Sigma\pi\pi$ branching ratio; it may well be the $\Sigma(1670)$ produced at larger angles (see TIMMERMANS 76). The other state, the $\Sigma(1660)P_{11}$, has different quantum numbers, its $\Sigma\pi/\Sigma\pi\pi$ branching ratio is unknown, and its relation to the produced $\Sigma(1670)$ states is obscure.

$\boxed{\Sigma(1670)\ D_{13}}$

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Results from production experiments are listed separately in the next entry.

$\Sigma(1670)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1665 to 1685 (≈ 1670) OUR ESTIMATE				
1665.1 ± 4.1	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1682 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1670 ± 6	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
1685 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1659 $^{+12}_{-5}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ± 2	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1667 or 1668	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1650	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
1671 ± 3	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
1655 ± 2	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
40 to 80 (≈ 60) OUR ESTIMATE				
65.0 ± 7.3	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
79 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
56 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
50 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
56 ± 3	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
85 ± 25	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
32 ± 11	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
79 ± 6	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
46 or 46	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
44 ± 11	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
76 ± 5	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	7–13 %
Γ_2	$\Lambda\pi$	5–15 %
Γ_3	$\Sigma\pi$	30–60 %
Γ_4	$\Lambda\pi\pi$	
Γ_5	$\Sigma\pi\pi$	
Γ_6	$\Sigma(1385)\pi$	
Γ_7	$\Sigma(1385)\pi$, *S*-wave	
Γ_8	$\Lambda(1405)\pi$	
Γ_9	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ $\qquad \Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.07 to 0.13 OUR ESTIMATE				
0.10 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.11 ± 0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.07 or 0.07	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda\pi$ $\qquad (\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.17 ± 0.03	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
0.13 ± 0.02	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
+0.10 ± 0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.06 ± 0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.09 ± 0.02	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.018 ± 0.060	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.05	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
0.08 ± 0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
0.17 ± 0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma\pi$ $\qquad (\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.20 ± 0.02	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
+0.21 ± 0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20 ± 0.01	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
+0.21 ± 0.03	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.18 or +0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Gamma(\Lambda\pi\pi)/\Gamma_{\rm total}$ $\qquad \Gamma_4/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.11	ARMENTEROS	68E	HBC	$K^- p$ (Γ_1=0.09)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma(1385)\pi$, *S*-wave $\qquad (\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.11 ± 0.03	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17 ± 0.02	[3] SIMS	68	DBC	$K^- N \to \Lambda\pi\pi$

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ $\qquad \Gamma_5/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.14	[4] ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma(\Lambda(1405)\pi)/\Gamma_{\rm total}$ $\qquad \Gamma_8/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma_i\Gamma_f/\Gamma^2_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1405)\pi$ $\qquad \Gamma_1\Gamma_8/\Gamma^2$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.007 ± 0.002	[5] BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	BERLEY	69	HBC	$K^- p$ 0.6–0.82 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ $\qquad \Gamma_8/\Gamma_6$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.23 ± 0.08	BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1520)\pi$ $\qquad (\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.081 ± 0.016	[6] CAMERON	77	DPWA	*P*-wave decay

$\Sigma(1670)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] Results are with and without an S_{11} $\Sigma(1620)$ in the fit.

[3] SIMS 68 uses only cross-section data. Result used as upper limit only.

[4] Ratio only for $\Sigma 2\pi$ system in $I = 1$, which cannot be $\Sigma(1385)$.

[5] Assuming the $\Lambda(1405)\pi$ cross-section bump is due only to $3/2^-$ resonance.

[6] The CAMERON 77 upper limit on *F*-wave decay is 0.03.

$\Sigma(1670)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BRUCKER	70	Duke Conf. 155	+Harrison, Sims, Albright, Chandler+	(FSU) I
BERLEY	69	PL 30B 430	+Hart, Rahm, Willis, Yamamoto	(BNL)
ARMENTEROS	68E	PL 28B 521	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFTS, BRAN)

$\Sigma(1670)$ Bumps

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the preceding entry.

Probably there are two states at the same mass with the same quantum numbers, one decaying to $\Sigma\pi$ and $\Lambda\pi$, the other to $\Lambda(1405)\pi$. See the note in front of the preceding entry.

$\Sigma(1670)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
≈ 1670 OUR ESTIMATE					
1670± 4		[1] CARROLL 76	DPWA		Isospin-1 total σ
1675±10		[2] HEPP 76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
1665± 1		APSELL 74	HBC		$K^- p$ 2.87 GeV/c
1688± 2 or 1683 ± 5	1200	BERTHON 74	HBC	0	Quasi-2-body σ
1670± 6		AGUILAR-... 70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
1668±10		AGUILAR-... 70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
1660±10		ALVAREZ 63	HBC	+	$K^- p$ 1.51 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1668±10	150	[3] FERRERSORIA 81	OMEG	−	$\pi^- p$ 9,12 GeV/c
1655 to 1677		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
1665± 5		BUGG 68	CNTR		$K^- p$, d total σ
1661± 9	70	PRIMER 68	HBC	+	See BARNES 69E
1685		ALEXANDER 62C	HBC	−0	$\pi^- p$ 2–2.2 GeV/c

$\Sigma(1670)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
67.0± 2.4		APSELL 74	HBC		$K^- p$ 2.87 GeV/c
110 ±12		AGUILAR-... 70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
135 $^{+40}_{-30}$		AGUILAR-... 70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
40 ±10		ALVAREZ 63	HBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
90 ±20	150	[3] FERRERSORIA 81	OMEG	−	$\pi^- p$ 9,12 GeV/c
52		[1] CARROLL 76	DPWA		Isospin-1 total σ
48 to 63		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
30 ±15		BUGG 68	CNTR		
60 ±20	70	PRIMER 68	HBC	+	See BARNES 69E
45		ALEXANDER 62C	HBC	−0	

$\Sigma(1670)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma\pi\pi$
Γ_6	$\Sigma(1385)\pi$
Γ_7	$\Lambda(1405)\pi$

$\Sigma(1670)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — Γ_1/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<0.03		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
<0.10		BERTHON 74	HBC	0	Quasi-2-body σ
<0.2		AGUILAR-... 70B	HBC		
<0.26		BARNES 69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.025		BUGG 68	CNTR	0	Assuming $J = 3/2$
<0.24	0	PRIMER 68	HBC	+	$K^- p$ 4.6–5 GeV/c
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
<0.19	0	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
≥ 0.5 ±0.25		SMITH 63	HBC	−0	

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ — Γ_2/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.76±0.09		ESTES 74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
0.45±0.15		BARNES 69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.15±0.07		HUWE 69	HBC	+	
0.11±0.06	33	BUTTON-... 68	HBC	+	$K^- p$ 1.7 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
≤ 0.45±0.07		TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
0.55±0.11		BERTHON 74	HBC	0	Quasi-2-body σ
0	0	PRIMER 68	HBC	+	See BARNES 69E
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
1.2	130	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
1.2		SMITH 63	HBC	−0	

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<0.6		LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
0.56	90	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c
0.17		SMITH 63	HBC	−0	

$\Gamma(\Sigma\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
largest at small angles		ESTES 74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.2		[2] HEPP 76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
0.56	180	ALVAREZ 63	HBC	+	$K^- p$ 1.15 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi)$ — Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.8 ±0.3 to 0.02 ± 0.07		[3,4] TIMMERMANS 76	HBC	+	$K^- p$ 4.2 GeV/c
largest at small angles		ESTES 74	HBC	±	$K^- p$ 2.1,2.6 GeV/c
3.0 ±1.6	50	LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.58±0.20	17	PRIMER 68	HBC	+	See BARNES 69E

$\Gamma(\Sigma\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_3/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
varies with prod. angle	[5] APSELL 74	HBC	+	$K^- p$ 2.87 GeV/c
1.39±0.16	BERTHON 74	HBC	0	Quasi-2-body σ
2.5 to 0.24	[4] EBERHARD 69	HBC		$K^- p$ 2.6 GeV/c
<0.4	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c
0.30±0.15	LONDON 66	HBC	+	$K^- p$ 2.25 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_7/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.97±0.08	TIMMERMANS 76	HBC		$K^- p$ 4.2 GeV/c
1.00±0.02	APSELL 74	HBC		$K^- p$ 2.87 GeV/c
$0.90^{+0.10}_{-0.16}$	EBERHARD 65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_7/Γ_6

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
<0.8	EBERHARD 65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_4/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.35±0.2	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_2/Γ_5

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
<0.2	BIRMINGHAM 66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ — $\Gamma_2/(\Gamma_2+\Gamma_3)$

VALUE	DOCUMENT ID	TECN
<0.6	AGUILAR-... 70B	HBC

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Sigma\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
≤ 0.21±0.05	TIMMERMANS 76	HBC	$K^- p$ 4.2 GeV/c

$\Sigma(1670)$ QUANTUM NUMBERS (PRODUCTION EXPERIMENTS)

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$J^P = 3/2^-$	400	BUTTON-... 68	HBC	±	$\Sigma^0\pi$
$J^P = 3/2^-$		EBERHARD 67	HBC	+	$\Lambda(1405)\pi$
$J^P = 3/2^+$		LEVEQUE 65	HBC		$\Lambda(1405)\pi$

$\Sigma(1670)$ FOOTNOTES

[1] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.23$.

[2] Enhancements in $\Sigma\pi$ and $\Sigma\pi\pi$ cross sections.

[3] Backward production in the $\Lambda\pi^- K^+$ final state.

[4] Depending on production angle.

[5] APSELL 74, ESTES 74, and TIMMERMANS 76 find strong branching ratio dependence on production angle, as in earlier production experiments.

$\Sigma(1670)$ REFERENCES (PRODUCTION EXPERIMENTS)

FERRERSORIA 81 NP B178 373 +Treille, Rivet, Volte+ (CERN, CDEF, EPOL, LALO)
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76 NP B115 82 +Braun, Grimm, Stroebele+ (CERN, HEID, MPIM) I
TIMMERMANS 76 NP B112 77 +Engelen+ (NIJM, CERN, AMST, OXF) JP
APSELL 74 PR D10 1419 +Ford, Gourevitch+ (BRAN, UMD, SYRA, TUFTS) I
BERTHON 74 NC 21A 146 +Tristram+ (CDEF, RHEL, SACL, STRB)
ESTES 74 Thesis LBL-3827 (LBL)
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
BARNES 69E BNL 13823 +Chung, Eisner, Flaminio+ (BNL, SYRA)
EBERHARD 69 PRL 22 200 +Friedman, Pripstein, Ross (LRL)
HUWE 69 PR 180 1824 (LRL)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
BUTTON-... 68 PRL 21 1123 Button-Shafer (MASA, LRL) JP
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL)
EBERHARD 67 PR 163 1446 +Pripstein, Shively, Kruse, Swanson (LRL, ILL) IJP
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IJ
EBERHARD 65 PRL 14 466 +Shively, Ross, Siegal, Ficenec+ (LRL, ILL) I
LEVEQUE 65 PL 18 69 + (SACL, EPOL, GLAS, LOIC, OXF, RHEL) JP
ALVAREZ 63 PRL 10 184 +Alston, Ferro-Luzzi, Huwe+ (LRL) I
SMITH 63 Athens Conf. 67 (LRL)
ALEXANDER 62C CERN Conf. 320 +Jacobs, Kalbfleisch, Miller+ (LRL) I

$\Sigma(1690)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the note preceding the $\Sigma(1670)$ Listings. Seen in production experiments only, mainly in $\Lambda\pi$.

$\Sigma(1690)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1690 OUR ESTIMATE						
1698±20	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1707±20	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1698±20	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
1682± 2	46	BLUMENFELD	69	HBC	+	$K^0_L p$
1700±20		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
1694±24	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
1700± 6		[4] SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
1715±12	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
240± 60	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
130^{+100}_{-60}	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
142± 40	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
25± 10	46	BLUMENFELD	69	HBC	+	$K^0_L p$
130± 25		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
105± 35	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
62± 14		[4] SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
100± 35	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Sigma(1385)\pi$
Γ_5	$\Lambda\pi\pi$ (including $\Sigma(1385)\pi$)

$\Sigma(1690)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.2		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.4±0.25	18	COLLEY	67	HBC	+	6/30 events

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.4	90	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.3±0.3		COLLEY	67	HBC	+	4/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c

$\Gamma(\Lambda\pi\pi(\text{including}\ \Sigma(1385)\pi))/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.0±0.6	BLUMENFELD	69	HBC	+	31/15 events
0.5±0.25	COLLEY	67	HBC	+	15/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi\pi(\text{including}\ \Sigma(1385)\pi))$ Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
large	SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
small	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] From $\pi^+ p \rightarrow (\Lambda\pi^+)K^+$. $J > 1/2$ is not required by the data.

[2] From $\pi^+ p \rightarrow (\Lambda\pi^+)(K\pi)^+$. $J > 1/2$ is indicated, but large background precludes a definite conclusion.

[3] See the $\Sigma(1670)$ Listings. AGUILAR-BENITEZ 70B with three times the data of PRIMER 68 find no evidence for the $\Sigma(1690)$.

[4] This analysis, which is difficult and requires several assumptions and shows no unambiguous $\Sigma(1690)$ signal, suggests $J^P = 5/2^+$. Such a state would lead all previously known Y^* trajectories.

$\Sigma(1690)$ REFERENCES (PRODUCTION EXPERIMENTS)

GODDARD 79 PR D19 1350 +Key, Luste, Prentice, Yoon, Gordon+ (TNTO, BNL) IJ
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
ADERHOLZ 69 NP B11 259 +Bartsch+ (AACH3, BERL, CERN, JAGL, WARS) I
BLUMENFELD 69 PL 29B 58 +Kalbfleisch (BNL) I
MOTT 69 PR 177 1966 +Ammar, Davis, Kropac, Slate+ (NWES, ANL) I
Also 67 PRL 18 266 Derrick, Fields, Loken, Ammar+ (ANL, NWES) I
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL) I
SIMS 68 PRL 21 1413 +Albright, Bartley, Meer+ (FSU, TUFTS, BRAN) I
COLLEY 67 PL 24B 489 (BIRM, GLAS, LOIC, MUNI, OXF, RHEL) I

$\Sigma(1750)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

There is evidence for this state in many partial-wave analyses, but with wide variations in the mass, width, and couplings. The latest analyses indicated significant couplings to $N\overline{K}$ and $\Lambda\pi$, as well as to $\Sigma\eta$ whose threshold is at 1746 MeV (JONES 74).

$\Sigma(1750)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1730 to 1800 (≈ 1750) OUR ESTIMATE				
1756±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1770±10	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1770±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1800 or 1813	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1715±10	[2] CARROLL	76	DPWA	isospin-1 total σ
1730	DEBELLEFON	76	IPWA	$K^- p \rightarrow \Lambda\pi^0$
1780±30	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 1)
1700±30	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 2)
1697^{+20}_{-10}	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
1785±12	CHU	74	DBC	Fits $\sigma(K^- n \rightarrow \Sigma^-\eta)$
1760± 5	[3] JONES	74	HBC	Fits $\sigma(K^- p \rightarrow \Sigma^0\eta)$
1739±10	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

$\Sigma(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 160 (≈ 90) OUR ESTIMATE				
64±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
161±20	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
60±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel

• • • We do not use the following data for averages, fits, limits, etc. • • •				
117 or 119	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
10	[2] CARROLL	76	DPWA	Isospin-1 total σ
110	DEBELLEFON	76	IPWA	$K^- p \rightarrow \Lambda\pi^0$
140±30	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 1)
160±50	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 2)
66^{+14}_{-12}	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
89±33	CHU	74	DBC	Fits $\sigma(K^- n \rightarrow \Sigma^- \eta)$
92± 7	[3] JONES	74	HBC	Fits $\sigma(K^- p \rightarrow \Sigma^0 \eta)$
108±20	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

$\Sigma(1750)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–40 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	<8 %
Γ_4	$\Sigma\eta$	15–55 %
Γ_5	$\Sigma(1385)\pi$	
Γ_6	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1750)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.4 OUR ESTIMATE				
0.14±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.33±0.05	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15±0.03	GOPAL	77	DPWA	See GOPAL 80
0.06 or 0.05	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1750) \rightarrow \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.09	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12	DEBELLEFON	76	IPWA	$K^- p \rightarrow \Lambda\pi^0$
−0.12 ±0.02	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 1)
−0.13 ±0.03	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 2)
−0.13 ±0.04	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
−0.120±0.077	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1750) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.06 or +0.06	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.13±0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1750) \rightarrow \Sigma\eta$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.23±0.01	[3] JONES	74	HBC	Fits $\sigma(K^- p \rightarrow \Sigma^0 \eta)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	CLINE	69	DBC	Threshold bump

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1750) \rightarrow \Sigma(1385)\pi$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18±0.15	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1750) \rightarrow \Lambda(1520)\pi$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032±0.021	CAMERON	77	DPWA	P-wave decay

$\Sigma(1750)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] A total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.30$.

[3] An S-wave Breit-Wigner fit to the threshold cross section with no background and errors statistical only.

$\Sigma(1750)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
CHU	74	NC 20A 35	+Bartley+	(PLAT, TUFTS, BRAN) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
JONES	74	NP B73 141		(CHIC) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
CLINE	69	LNC 2 407	+Laumann, Mapp	(WISC)

$\Sigma(1770)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Evidence for this state now rests solely on solution 1 of BAILLON 75, (see the footnotes) but the $\Lambda\pi$ partial-wave amplitudes of this solution are in disagreement with amplitudes from most other $\Lambda\pi$ analyses.

$\Sigma(1770)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1770 OUR ESTIMATE				
1738±10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
1770±20	[2] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
1772	[3] KANE	72	DPWA	$K^- p \rightarrow \Sigma\pi$

$\Sigma(1770)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
72±10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
80±30	[2] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
80	[3] KANE	72	DPWA	$K^- p \rightarrow \Sigma\pi$

$\Sigma(1770)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1770)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.04	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1770) \rightarrow \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.08±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1770) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.108	[3] KANE	72	DPWA	$K^- p \rightarrow \Sigma\pi$

$\Sigma(1770)$ FOOTNOTES

[1] Required to fit the isospin-1 total cross section of CARROLL 76 in the $\overline{K}N$ channel. The addition of new $K^- p$ polarization and $K^- n$ differential cross-section data in GOPAL 80 find it to be more consistent with the $\Sigma(1660)\ P_{11}$.

[2] From solution 1 of BAILLON 75; not present in solution 2.

[3] Not required in KANE 74, which supersedes KANE 72.

$\Sigma(1770)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
KANE	74	LBL-2452		(LBL) IJP
KANE	72	PR D5 1583		(LBL)

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$ Status: ∗∗∗∗

Discovered by GALTIERI 63, this resonance plays the same role as cornerstone for isospin-1 analyses in this region as the $\Lambda(1820)$ does in the isospin-0 channel.

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Σ(1775) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1770 to 1780 (≈ 1775) OUR ESTIMATE				
1778± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1777± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1774± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1775±10	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1774±10	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1772± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1772 or 1777	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1765	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

Σ(1775) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
105 to 135 (≈ 120) OUR ESTIMATE				
137±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
116±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
130±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
125±15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
146±18	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
154±10	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
102 or 103	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

Σ(1775) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	37–43%
Γ_2	$\Lambda\pi$	14–20%
Γ_3	$\Sigma\pi$	2–5%
Γ_4	$\Sigma(1385)\pi$	8–12%
Γ_5	$\Sigma(1385)\pi$, D-wave	
Γ_6	$\Lambda(1520)\pi$	17–23%
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

CONSTRAINED FIT INFORMATION

An overall fit to 8 branching ratios uses 16 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 63.9 for 12 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cccc} x_2 & -30 & & & \\ x_3 & -17 & -21 & & \\ x_4 & -37 & -49 & -14 & \\ x_6 & -81 & 6 & 8 & 16 \\ \hline & x_1 & x_2 & x_3 & x_4 \end{array}$$

Σ(1775) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances. Also, the errors quoted do not include uncertainties due to the parametrization used in the partial-wave analyses and are thus too small.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.37 to 0.43 OUR ESTIMATE				
0.45 ±0.04 OUR FIT Error includes scale factor of 3.1.				
0.391±0.017 OUR AVERAGE				
0.40 ±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.37 ±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41 ±0.03	GOPAL	77	DPWA	See GOPAL 80
0.37 or 0.36	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.305±0.018 OUR FIT Error includes scale factor of 2.4.				
−0.262±0.015 OUR AVERAGE				
−0.28 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.25 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.28\ ^{+0.04}_{-0.05}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.259±0.048	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.29 or −0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.30	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.105±0.025 OUR FIT Error includes scale factor of 3.1.				
0.098±0.016 OUR AVERAGE Error includes scale factor of 1.8.				
+0.13 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.09 ±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.315±0.010 OUR FIT Error includes scale factor of 1.5.				
0.303±0.009 OUR AVERAGE Signs on measurements were ignored.				
−0.305±0.010	[2] CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.31 ±0.02	BARLETTA	72	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.27 ±0.03	ARMENTEROS	65C	HBC	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.211±0.022 OUR FIT Error includes scale factor of 2.8.				
0.188±0.010 OUR AVERAGE Signs on measurements were ignored.				
−0.184±0.011	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.20 ±0.02	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.32 ±0.06	SIMS	68	DBC	$K^-N \to \Lambda\pi\pi$
0.24 ±0.03	ARMENTEROS	67C	HBC	$K^-p \to \Lambda\pi\pi$

$\Gamma(\Lambda\pi)/\Gamma(N\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.46±0.09 OUR FIT Error includes scale factor of 2.9.				
0.33±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.12	[4] ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$\Gamma(\Sigma(1385)\pi)/\Gamma(N\overline{K})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.07 OUR FIT Error includes scale factor of 3.6.				
0.25±0.09	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Lambda(1520)\pi)/\Gamma(N\overline{K})$ — Γ_6/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.49±0.11 OUR FIT Error includes scale factor of 3.5.				
0.28±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

Σ(1775) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] This rate combines P-wave- and F-wave decays. The CAMERON 77 results for the separate P-wave- and F-wave decays are −0.303 ± 0.010 and −0.037 ± 0.014. The published signs have been changed here to be in accord with the baryon-first convention.

[3] The CAMERON 78 upper limit on G-wave decay is 0.03.

[4] For about 3/4 of this, the $\Sigma\pi$ system has $I = 0$ and is almost entirely $\Lambda(1520)$. For the rest, the $\Sigma\pi$ has $I = 1$, which is about what is expected from the known $\Sigma(1775) \to \Sigma(1385)\pi$ rate, as seen in $\Lambda\pi\pi$.

Σ(1775) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP

DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BARLETTA	72	NP B40 45		(EFI) IJP
Also	66	PRL 17 841	Fenster, Gelfand, Harmsen+	(CHIC, ANL, CERN) IJP
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFTS, BRAN)
ARMENTEROS	67C	ZPHY 202 486	+Ferro-Luzzi+	(CERN, HEID, SACL)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL) IJP
GALTIERI	63	PL 6 296	+Hussain, Tripp	(LRL) IJ

$\Sigma(1840)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗

OMITTED FROM SUMMARY TABLE

For the time being, we list together here all resonance claims in the P_{13} wave between 1700 and 1900 MeV.

$\Sigma(1840)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1840 OUR ESTIMATE				
1798 or 1802	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1720± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1925±200	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1840± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
93 or 93	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
65^{+50}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1840)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0 or 0	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.37±0.13	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1840) \to \Lambda\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 or +0.03	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.11 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.06 ±0.04	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.122±0.078	DEVENISH	74B		Fixed-t dispersion rel.
0.20 ±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1840) \to \Sigma\pi$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04 or −0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.15±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] From solution 1 of BAILLON 75; not present in solution 2.

$\Sigma(1840)$ REFERENCES

MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP

$\Sigma(1880)$ P_{11}

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

A P_{11} resonance is suggested by several partial-wave analyses, but with wide variations in the mass and other parameters. We list here all claims which lie well above the P_{11} $\Sigma(1770)$.

$\Sigma(1880)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1880 OUR ESTIMATE				
1826±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1870±10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
1847 or 1863	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1960±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1985±50	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1898	[3] LEA	73	DPWA	Multichannel K-matrix
~ 1850	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
1950±50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
1920±30	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
1850	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1882±40	SMART	68	DPWA	$K^- N \to \Lambda\pi$

$\Sigma(1880)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
86± 15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
80± 10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
216 or 220	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
260± 40	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
220±140	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
222	[3] LEA	73	DPWA	Multichannel K-matrix
~ 30	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
200± 50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
170± 40	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
200	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
222±150	SMART	68	DPWA	$K^- N \to \Lambda\pi$

$\Sigma(1880)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$N\overline{K}^*(892)$, S=1/2, P-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, P-wave

$\Sigma(1880)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27 or 0.27	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.31	[3] LEA	73	DPWA	Multichannel K-matrix
0.20	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
0.22	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1880) \to \Lambda\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24 or −0.24	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.05\ ^{+0.07}_{-0.02}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.169±0.119	DEVENISH	74B		Fixed-t dispersion rel.
−0.30	[3] LEA	73	DPWA	Multichannel K-matrix
−0.09 ±0.04	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
−0.14 ±0.03	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
−0.11 ±0.03	SMART	68	DPWA	$K^- N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1880) \to \Sigma\pi$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
+0.30 or +0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	[3] LEA	73	DPWA	Multichannel K-matrix

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, S=1/2, P-wave **$(\Gamma_1\Gamma_4)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID		TECN	COMMENT
−0.05±0.03	[4] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, $S=3/2$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.11\pm0.03$	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Sigma(1880)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] From solution 1 of BAILLON 75; not present in solution 2.

[3] Only unconstrained states from table 1 of LEA 73 are listed.

[4] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(1880)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LEA	73	NP B56 77	+Martin, Moorhouse+	(RHEL, LOUC, GLAS, AARH) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP
BAILEY	69	Thesis UCRL 50617		(LLL) IJP
SMART	68	PR 169 1330		(LRL) IJP

$\Sigma(1915)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66. For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions in this region used to be listed in in a separate entry immediately following. They may be found in our 1986 edition Physics Letters **170B** (1986).

$\Sigma(1915)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1935 (≈ 1915) OUR ESTIMATE				
1937 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
$1894\pm\ 5$	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
$1909\pm\ 5$	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
1920 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$1900\pm\ 4$	[2] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
1920 ± 30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1914 ± 10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
1920^{+15}_{-20}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
$1920\pm\ 5$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1925 or 1933	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1915	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1915)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 160 (≈ 120) OUR ESTIMATE				
161 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
107 ± 14	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
85 ± 13	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
130 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
75 ± 14	[2] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
70 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
85 ± 15	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
102 ± 18	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
162 ± 25	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
171 or 173	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
60	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1915)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–15 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	<5 %
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$\Sigma(1385)\pi$, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1915)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.03 ± 0.02	[4] GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.11 ± 0.04	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.08 or 0.08	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$-0.09\ \pm0.03$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$-0.10\ \pm0.01$	[2] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
$-0.06\ \pm0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.09\ \pm0.02$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
-0.087 ± 0.056	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.09 or -0.09	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
-0.10	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.01	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
-0.15 ± 0.02	[1] CORDEN	77C		$K^-n \to \Sigma\pi$
-0.19 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.16 ± 0.03	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.05 or -0.05	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.01	CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.039\pm0.009$	[5] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$\Sigma(1915)$ FOOTNOTES

[1] The two entries for CORDEN 77C are from two different acceptable solutions.

[2] Preferred solution 3; see CORDEN 76 for other possibilities.

[3] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[4] The mass and width are fixed to the GOPAL 77 values due to the low elasticity.

[5] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(1915)$ REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)

$\Sigma(1940)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Not all analyses require this state. It is not required by the GOYAL 77 analysis of $K^- n \to (\Sigma\pi)^-$ nor by the GOPAL 80 analysis of $K^- n \to K^- n$. See also HEMINGWAY 75.

$\Sigma(1940)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1950 (≈ 1940) OUR ESTIMATE				
1920±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1950±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1949^{+40}_{-60}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1935±80	KANE	74	DPWA	$K^- p \to \Sigma\pi$
1940±20	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
1950±20	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1886 or 1893	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1940	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$, F_{17} wave

$\Sigma(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 300 (≈ 220) OUR ESTIMATE				
170±25	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
300±80	GOPAL	77	DPWA	$\overline{K}N$ multichannel
150±75	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
160^{+70}_{-40}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
330±80	KANE	74	DPWA	$K^- p \to \Sigma\pi$
60±20	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
70^{+30}_{-20}	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
157 or 159	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Sigma(1940)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<20 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, S-wave	
Γ_6	$\Lambda(1520)\pi$	seen
Γ_7	$\Lambda(1520)\pi$, P-wave	
Γ_8	$\Lambda(1520)\pi$, F-wave	
Γ_9	$\Delta(1232)\overline{K}$	seen
Γ_{10}	$\Delta(1232)\overline{K}$, S-wave	
Γ_{11}	$\Delta(1232)\overline{K}$, D-wave	
Γ_{12}	$N\overline{K}^*(892)$	seen
Γ_{13}	$N\overline{K}^*(892)$, S=3/2, S-wave	

$\Sigma(1940)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.2 OUR ESTIMATE				
<0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.14 or 0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.04 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.05\ ^{+0.03}_{-0.02}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.153±0.070	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.15 or −0.14	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.08±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.14±0.04	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.16 or +0.16	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.03	CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
−0.11±0.04	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.062±0.021	CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
−0.08 ±0.04	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, S-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.05	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, D-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14±0.05	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.066±0.025	[2] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1940) \to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.02	[3] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Sigma(1940)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

[3] Upper limits on the D_1 and D_3 waves are each 0.03.

$\Sigma(1940)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH)
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEIDH) IJP

$\Sigma(2000)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all reported S_{11} states lying above the $\Sigma(1750)\ S_{11}$.

$\Sigma(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1944±15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1955±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1755 or 1834	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
2004±40	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
215±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
170±40	GOPAL	77	DPWA	$\overline{K}N$ multichannel
413 or 450	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
116±40	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda(1520)\pi$
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Sigma(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.51 ± 0.05	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.44 ± 0.05	GOPAL	77	DPWA	See GOPAL 80
0.62 or 0.57	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2000) \rightarrow \Lambda\pi$ $\qquad(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.08 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.19 or -0.18	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
$+0.07^{+0.02}_{-0.01}$	VANHORN	75	DPWA	$K^-p \rightarrow \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2000) \rightarrow \Sigma\pi$ $\qquad(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$+0.20\pm0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.26$ or $+0.24$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2000) \rightarrow \Lambda(1520)\pi$ $\qquad(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$+0.081\pm0.021$	[2] CAMERON	77	DPWA	P-wave decay

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2000) \rightarrow N\overline{K}^*(892)$, S=1/2, S-wave $\qquad(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$+0.10\pm0.02$	[2] CAMERON	78B	DPWA	$K^-p \rightarrow N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2000) \rightarrow N\overline{K}^*(892)$, S=3/2, D-wave $\qquad(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.07 ± 0.03	CAMERON	78B	DPWA	$K^-p \rightarrow N\overline{K}^*$

$\Sigma(2000)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(2000)$ REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
CAMERON 78B NP B146 327 +Franek, Gopal, Kalmus, McPherson+ (RHEL, LOIC) IJP
CAMERON 77 NP B131 399 +Franek, Gopal, Kalmus, McPherson+ (RHEL, LOIC) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
BAILLON 75 NP B94 39 +Litchfield (CERN, RHEL) IJP
VANHORN 75 NP B87 145 (LBL) IJP
Also 75B NP B87 157 VanHorn (LBL) IJP

$\Sigma(2030)$ F_{17}

$I(J^P) = 1(\frac{7}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions around 2030 MeV may be found in our 1984 edition, Reviews of Modern Physics **56** No. 2 Pt. II (1984).

$\Sigma(2030)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2025 to 2040 (≈ 2030) OUR ESTIMATE				
$2036\pm\ 5$	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
2038 ± 10	CORDEN	77B		$K^-N \rightarrow N\overline{K}^*$
$2040\pm\ 5$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$2030\pm\ 3$	[1] CORDEN	76	DPWA	$K^-n \rightarrow \Lambda\pi^-$
2035 ± 15	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
2038 ± 10	HEMINGWAY	75	DPWA	$K^-p \rightarrow \overline{K}N$
2042 ± 11	VANHORN	75	DPWA	$K^-p \rightarrow \Lambda\pi^0$
$2020\pm\ 6$	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
2035 ± 10	LITCHFIELD	74B	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$
2020 ± 30	LITCHFIELD	74C	DPWA	$K^-p \rightarrow \Delta(1232)\overline{K}$
2025 ± 10	LITCHFIELD	74D	DPWA	$K^-p \rightarrow \Lambda(1820)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2027 to 2057	GOYAL	77	DPWA	$K^-N \rightarrow \Sigma\pi$
2030	DEBELLEFON	76	IPWA	$K^-p \rightarrow \Lambda\pi^0$

$\Sigma(2030)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
150 to 200 (≈ 180) OUR ESTIMATE				
172 ± 10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
137 ± 40	CORDEN	77B		$K^-N \rightarrow N\overline{K}^*$
190 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$201\pm\ 9$	[1] CORDEN	76	DPWA	$K^-n \rightarrow \Lambda\pi^-$
180 ± 20	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
172 ± 15	HEMINGWAY	75	DPWA	$K^-p \rightarrow \overline{K}N$
178 ± 13	VANHORN	75	DPWA	$K^-p \rightarrow \Lambda\pi^0$
$111\pm\ 5$	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
160 ± 20	LITCHFIELD	74B	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$
200 ± 30	LITCHFIELD	74C	DPWA	$K^-p \rightarrow \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
260	DECLAIS	77	DPWA	$\overline{K}N \rightarrow \overline{K}N$
126 to 195	GOYAL	77	DPWA	$K^-N \rightarrow \Sigma\pi$
160	DEBELLEFON	76	IPWA	$K^-p \rightarrow \Lambda\pi^0$
70 to 125	LITCHFIELD	74D	DPWA	$K^-p \rightarrow \Lambda(1820)\pi^0$

$\Sigma(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	17–23 %
Γ_2	$\Lambda\pi$	17–23 %
Γ_3	$\Sigma\pi$	5–10 %
Γ_4	ΞK	<2 %
Γ_5	$\Sigma(1385)\pi$	5–15 %
Γ_6	$\Sigma(1385)\pi$, F-wave	
Γ_7	$\Lambda(1520)\pi$	10–20 %
Γ_8	$\Lambda(1520)\pi$, D-wave	
Γ_9	$\Lambda(1520)\pi$, G-wave	
Γ_{10}	$\Delta(1232)\overline{K}$	10–20 %
Γ_{11}	$\Delta(1232)\overline{K}$, F-wave	
Γ_{12}	$\Delta(1232)\overline{K}$, H-wave	
Γ_{13}	$N\overline{K}^*(892)$	<5 %
Γ_{14}	$N\overline{K}^*(892)$, S=1/2, F-wave	
Γ_{15}	$N\overline{K}^*(892)$, S=3/2, F-wave	
Γ_{16}	$\Lambda(1820)\pi$, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2030)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 to 0.23 OUR ESTIMATE				
0.19±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.18±0.03	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.02	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20 ±0.01	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
+0.18 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.20 ±0.01	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
+0.195±0.053	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09 ±0.01	[2] CORDEN	77C		$K^-n \to \Sigma\pi$
−0.06 ±0.01	[2] CORDEN	77C		$K^-n \to \Sigma\pi$
−0.15 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.10 ±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.085±0.02	[3] GOYAL	77	DPWA	$K^-N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Xi K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.023	MULLER	69B	DPWA	$K^-p \to \Xi K$
<0.05	BURGUN	68	DPWA	$K^-p \to \Xi K$
<0.05	TRIPP	67	RVUE	$K^-p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1820)\pi$, *P*-wave $(\Gamma_1\Gamma_{16})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.02	CORDEN	75B	DBC	$K^-n \to N\overline{K}\pi^-$
0.18±0.04	LITCHFIELD	74D	DPWA	$K^-p \to \Lambda(1820)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *D*-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.114±0.010	[4] CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.14 ±0.03	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ±0.03	[5] CORDEN	75B	DBC	$K^-n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *G*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.146±0.010	[4] CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.02 ±0.02	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *F*-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.03	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17±0.03	[5] CORDEN	75B	DBC	$K^-n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *H*-wave $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00±0.02	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.153±0.026	[4] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=1/2, *F*-wave $(\Gamma_1\Gamma_{14})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06±0.03	[4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
−0.02±0.01	CORDEN	77B		$K^-d \to NN\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=3/2, *F*-wave $(\Gamma_1\Gamma_{15})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04±0.03	[6] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
−0.12±0.02	CORDEN	77B		$K^-d \to NN\overline{K}^*$

$\Sigma(2030)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities.
[2] The two entries for CORDEN 77C are from two different acceptable solutions.
[3] This coupling is extracted from unnormalized data.
[4] The published sign has been changed to be in accord with the baryon-first convention.
[5] An upper limit.
[6] The upper limit on the G_3 wave is 0.03.

$\Sigma(2030)$ REFERENCES

PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CORDEN	77B	NP B121 365	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
CORDEN	75B	NP B92 365	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74D	NP B74 12	+Hemingway, Baillon+	(CERN, HEIDH) IJP
MULLER	69B	Thesis UCRL 19372		(LRL)
BURGUN	68	NP B8 447	+Meyer, Pauli, Tallini+	(SACL, CDEF, RHEL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Sigma(2070)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

This state suggested by BERTHON 70B finds support in GOPAL 80 with new K^-p polarization and K^-n angular distributions. The very broad state seen in KANE 72 is not required in the later (KANE 74) analysis of $\overline{K}N \to \Sigma\pi$.

$\Sigma(2070)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2070 OUR ESTIMATE				
2051±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2057	KANE	72	DPWA	$K^-p \to \Sigma\pi$
2070±10	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(2070)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±30	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
906	KANE	72	DPWA	$K^-p \to \Sigma\pi$
140±20	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(2070)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$

$\Sigma(2070)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2070) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.104	KANE	72	DPWA	$K^-p \to \Sigma\pi$
+0.12 ±0.02	BERTHON	70B	DPWA	$K^-p \to \Sigma\pi$

Σ(2070) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
KANE	74	LBL-2452		(LBL)
KANE	72	PR D5 1583		(LBL)
BERTHON	70B	NP B24 417	+Vrana, Butterworth+	(CDEF, RHEL, SACL) IJP

$\Sigma(2080)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Suggested by some but not all partial-wave analyses across this region.

Σ(2080) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2080 OUR ESTIMATE			
2091± 7	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
2070 to 2120	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
2120±40	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
2140±40	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
2082± 4	COX 70	DPWA	See CORDEN 76
2070±30	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
186±48	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
100	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
240±50	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
200±50	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
87±20	COX 70	DPWA	See CORDEN 76
250±40	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

Σ(2080) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2080) \to \Lambda\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
−0.10±0.03	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
−0.10	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
−0.13±0.04	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1 and 2)
−0.16±0.03	COX 70	DPWA	See CORDEN 76
−0.09±0.03	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities, including a D_{15} at this mass.

Σ(2080) REFERENCES

CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
COX	70	NP B19 61	+Islam, Colley+	(BIRM, EDIN, GLAS, LOIC) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP

$\Sigma(2100)$ G_{17}

$I(J^P) = 1(\frac{7}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Σ(2100) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2100 OUR ESTIMATE			
2060±20	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$
2120±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
70±30	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$
135±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(2100) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2100) \to \Lambda\pi$ **$(\Gamma_1\Gamma_2)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
−0.07±0.02	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2100) \to \Sigma\pi$ **$(\Gamma_1\Gamma_3)^{1/2}/\Gamma$**

VALUE	DOCUMENT ID	TECN	COMMENT
+0.13±0.02	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) REFERENCES

BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Sigma(2250)$

$I(J^P) = 1(?^?)$ Status: ∗∗∗

Results from partial-wave analyses are too weak to warrant separating them from the production and cross-section experiments. LASINSKI 71 in $\overline{K}N$ using a Pomeron + resonances model, and DEBELLEFON 76, DEBELLEFON 77, and DEBELLEFON 78 in energy-dependent partial-wave analyses of $\overline{K}N \to \Lambda\pi$, $\Sigma\pi$, and $N\overline{K}$, respectively, suggest two resonances around this mass.

Σ(2250) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2210 to 2280 (≈ 2250) OUR ESTIMATE			
2270±50	DEBELLEFON 78	DPWA	D_5 wave
2210±30	DEBELLEFON 78	DPWA	G_9 wave
2275±20	DEBELLEFON 77	DPWA	D_5 wave
2215±20	DEBELLEFON 77	DPWA	G_9 wave
2300±30	[1] DEBELLEFON 75B	HBC	$K^- p \to \Xi^{*0} K^0$
2251^{+30}_{-20}	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
2280±14	AGUILAR-... 70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
2237±11	BRICMAN 70	CNTR	Total, charge exchange
2255±10	COOL 70	CNTR	$K^- p$, $K^- d$ total
2250± 7	BUGG 68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2260	DEBELLEFON 76	IPWA	D_5 wave
2215	DEBELLEFON 76	IPWA	G_9 wave
2250±20	LU 70	CNTR	$\gamma p \to K^+ Y^*$
2245	BLANPIED 65	CNTR	$\gamma p \to K^+ Y^*$
2299± 6	BOCK 65	HBC	$\overline{p}p$ 5.7 GeV/c

Σ(2250) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
60 to 150 (≈ 100) OUR ESTIMATE			
120 ± 40	DEBELLEFON 78	DPWA	D_5 wave
80 ± 20	DEBELLEFON 78	DPWA	G_9 wave
70 ± 20	DEBELLEFON 77	DPWA	D_5 wave
60 ± 20	DEBELLEFON 77	DPWA	G_9 wave
130 ± 20	[1] DEBELLEFON 75B	HBC	$K^- p \to \Xi^{*0} K^0$
192 ± 30	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
100 ± 20	AGUILAR-... 70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
164 ± 50	BRICMAN 70	CNTR	Total, charge exchange
230 ± 20	BUGG 68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •			
100	DEBELLEFON 76	IPWA	D_5 wave
140	DEBELLEFON 76	IPWA	G_9 wave
170	COOL 70	CNTR	$K^- p$, $K^- d$ total
125	LU 70	CNTR	$\gamma p \to K^+ Y^*$
150	BLANPIED 65	CNTR	$\gamma p \to K^+ Y^*$
21^{+17}_{-21}	BOCK 65	HBC	$\bar{p}p$ 5.7 GeV/c

Σ(2250) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\bar{K}$	<10 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$N\bar{K}\pi$	
Γ_5	$\Xi(1530)K$	

The above branching fractions are our estimates, not fits or averages.

Σ(2250) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\bar{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
<0.1 OUR ESTIMATE			
0.08 ± 0.02	DEBELLEFON 78	DPWA	D_5 wave
0.02 ± 0.01	DEBELLEFON 78	DPWA	G_9 wave

$(J+\frac{1}{2})\times\Gamma(N\bar{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.16 ± 0.12	BRICMAN 70	CNTR	Total, charge exchange
0.42	COOL 70	CNTR	$K^- p$, $K^- d$ total
0.47	BUGG 68	CNTR	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\bar{K} \to \Sigma(2250) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.16 ± 0.03	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$+0.11$	DEBELLEFON 76	IPWA	D_5 wave
-0.10	DEBELLEFON 76	IPWA	G_9 wave
-0.18	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$, G_9 wave

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\bar{K} \to \Sigma(2250) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$+0.06\pm0.02$	DEBELLEFON 77	DPWA	D_5 wave
-0.03 ± 0.02	DEBELLEFON 77	DPWA	G_9 wave
$+0.07$	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$, G_9 wave

$\Gamma(N\bar{K})/\Gamma(\Sigma\pi)$ Γ_1/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.18	BARNES 69	HBC	1 standard dev. limit

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.18	BARNES 69	HBC	1 standard dev. limit

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\bar{K} \to \Sigma(2250) \to \Xi(1530)K$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.18 ± 0.04	[1] DEBELLEFON 75B	HBC	$K^- p \to \Xi^{*0} K^0$

Σ(2250) FOOTNOTES

[1] Seen in the (initial and final state) D_5 wave. Isospin not determined.

Σ(2250) REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LASINSKI	71	NP B29 125		(EFI) IJP
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
COOL	70	PR D1 1887	+Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)
BARNES	69	PRL 22 479	+Flaminio, Montanet, Samios+	(BNL, SYRA)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
BLANPIED	65	PRL 14 741	+Greenberg, Hughes, Kitching, Lu+	(YALE, CEA)
BOCK	65	PL 17 166	+Cooper, French, Kinson+	(CERN, SACL)

Σ(2455) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is also some slight evidence for Y^* states in this mass region from the reaction $\gamma p \to K^+ X$ — see GREENBERG 68.

Σ(2455) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
≈ 2455 OUR ESTIMATE			
2455 ± 10	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
2455 ± 7	BUGG 68	CNTR	$K^- p$, $K^- d$ total

Σ(2455) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
140	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
100 ± 20	BUGG 68	CNTR	

Σ(2455) DECAY MODES

	Mode
Γ_1	$N\bar{K}$

Σ(2455) BRANCHING RATIOS

$(J+\frac{1}{2})\times\Gamma(N\bar{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.39	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
0.05 ± 0.05	[1] BRICMAN 70	CNTR	Total, charge exchange
0.3	BUGG 68	CNTR	

Σ(2455) FOOTNOTES

[1] Fit of total cross section given by BRICMAN 70 is poor in this region.

Σ(2455) REFERENCES

ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	67E	PRL 19 678	Abrams, Cool, Giacomelli, Kycia, Leontic+	(BNL)
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
GREENBERG	68	PRL 20 221	+Hughes, Lu, Minehart+	(YALE)

$\Sigma(2620)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Sigma(2620)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 2620 OUR ESTIMATE				
2542±22	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
2620±15	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

$\Sigma(2620)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
221±81	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
175	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

$\Sigma(2620)$ DECAY MODES

	Mode
Γ_1	$N \overline{K}$

$\Sigma(2620)$ BRANCHING RATIOS

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.32	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.36±0.12	BRICMAN	70	CNTR	Total, charge exchange

$\Sigma(2620)$ REFERENCES

DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
Also	67E	PRL 19 678	Abrams, Cool, Giacomelli, Kycia, Leontic+	(BNL)
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)

$\Sigma(3000)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen as an enhancement in $\Lambda\pi$ and $\overline{K}N$ invariant mass spectra and in the missing mass of neutrals recoiling against a K^0.

$\Sigma(3000)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
≈ 3000 OUR ESTIMATE					
3000	EHRLICH	66	HBC	0	$\pi^- p$ 7.91 GeV/c

$\Sigma(3000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

$\Sigma(3000)$ REFERENCES

EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN)

$\Sigma(3170)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen by AMIRZADEH 79 as a narrow 6.5-standard-deviation enhancement in the reaction $K^- p \to Y^{*+} \pi^-$ using data from independent high statistics bubble chamber experiments at 8.25 and 6.5 GeV/c. The dominant decay modes are multibody, multistrange final states and the production is via isospin-3/2 baryon exchange. Isospin 1 is favored.

Not seen in a $K^- p$ experiment in LASS at 11 GeV/c (ASTON 85B).

$\Sigma(3170)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 3170 OUR ESTIMATE					
3170±5	35	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<20	35	[1] AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K \overline{K} \pi$'s	seen
Γ_2	$\Sigma K \overline{K} \pi$'s	seen
Γ_3	$\Xi K \pi$'s	seen

$\Sigma(3170)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda K\overline{K}\pi\text{'s})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Sigma K\overline{K}\pi\text{'s})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Xi K\pi\text{'s})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Sigma(3170)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] Observed width consistent with experimental resolution.

$\Sigma(3170)$ REFERENCES (PRODUCTION EXPERIMENTS)

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
AMIRZADEH	79	PL 89B 125	+	(BIRM, CERN, GLAS, MSU, CURIN, CAVE+)
Also	80	Toronto Conf. 263	Kinson+	(BIRM, CERN, GLAS, MSU, CURIN)

Ξ BARYONS
$(S = -2, I = 1/2)$

$\Xi^0 = uss, \quad \Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

Ξ^0 MASS

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*
1314.9±0.6 OUR FIT				
1314.8±0.8 OUR AVERAGE				
1315.2±0.92	49	WILQUET	72	HLBC
1313.4±1.8	1	PALMER	68	HBC

$m_{\Xi^-} - m_{\Xi^0}$

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
6.4±0.6 OUR FIT					
6.3±0.7 OUR AVERAGE					
6.9±2.2	29	LONDON	66	HBC	
6.1±0.9	88	PJERROU	65B	HBC	
6.8±1.6	23	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.1±1.6	45	CARMONY	64B	HBC	See PJERROU 65B

Ξ^0 MEAN LIFE

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.90±0.09 OUR AVERAGE					
2.83±0.16	6300	[1] ZECH	77	SPEC	Neutral hyperon beam
$2.88^{+0.21}_{-0.19}$	652	BALTAY	74	HBC	1.75 GeV/c $K^- p$
$2.90^{+0.32}_{-0.27}$	157	[2] MAYEUR	72	HLBC	2.1 GeV/c K^-
$3.07^{+0.22}_{-0.20}$	340	DAUBER	69	HBC	
3.0 ±0.5	80	PJERROU	65B	HBC	
$2.5\ ^{+0.4}_{-0.3}$	101	HUBBARD	64	HBC	
$3.9\ ^{+1.4}_{-0.8}$	24	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.5\ ^{+1.0}_{-0.8}$	45	CARMONY	64B	HBC	See PJERROU 65B

[1] The ZECH 77 result is $\tau_{\Xi^0} = [2.77-(\tau_\Lambda-2.69)] \times 10^{-10}$ s, in which we use $\tau_\Lambda = 2.63 \times 10^{-10}$ s.

[2] The MAYEUR 72 value is modified by the erratum.

Ξ^0 MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*		*TECN*
−1.250±0.014 OUR AVERAGE				
−1.253±0.014	270k	COX	81	SPEC
−1.20 ±0.06	42k	BUNCE	79	SPEC

Ξ^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$\Lambda\pi^0$		(99.54±0.05) %		
Γ_2	$\Lambda\gamma$		(1.06±0.16) × 10^{-3}		
Γ_3	$\Sigma^0\gamma$		(3.5 ±0.4) × 10^{-3}		
Γ_4	$\Sigma^+ e^- \overline{\nu}_e$		< 1.1	× 10^{-3}	90%
Γ_5	$\Sigma^+ \mu^- \overline{\nu}_\mu$		< 1.1	× 10^{-3}	90%

$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 2$ forbidden ($S2$) modes

Γ_6	$\Sigma^- e^+ \nu_e$	SQ	< 9	× 10^{-4}	90%
Γ_7	$\Sigma^- \mu^+ \nu_\mu$	SQ	< 9	× 10^{-4}	90%
Γ_8	$p\pi^-$	$S2$	< 4	× 10^{-5}	90%
Γ_9	$pe^-\overline{\nu}_e$	$S2$	< 1.3	× 10^{-3}	
Γ_{10}	$p\mu^-\overline{\nu}_\mu$	$S2$	< 1.3	× 10^{-3}	

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 2 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 0.0 for 0 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cc} x_2 & -35 & \\ x_3 & -94 & 0 \\ \hline & x_1 & x_2 \end{array}$$

Ξ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi^0)$ **Γ_2/Γ_1**

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.06±0.16 OUR FIT					
1.06±0.12±0.11	116	JAMES	90	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5 ±5	1	YEH	74	HBC	Effective denom.=200

$\Gamma(\Sigma^0\gamma)/\Gamma(\Lambda\pi^0)$ **Γ_3/Γ_1**

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.6 ±0.4 OUR FIT						
3.56±0.42±0.10		85	TEIGE	89	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 8	90		BENSINGER	88	MPS2	$K^- W$ 6 GeV/c
<65	90	0–1	YEH	74	HBC	Effective denom.=60

$\Gamma(\Sigma^+ e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ **Γ_4/Γ_1**

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<7			HUBBARD	66	HBC	

$\Gamma(\Sigma^+ \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ **Γ_5/Γ_1**

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<7			HUBBARD	66	HBC	

$\Gamma(\Sigma^- e^+ \nu_e)/\Gamma(\Lambda\pi^0)$ **Γ_6/Γ_1**

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(\Sigma^- \mu^+ \nu_\mu)/\Gamma(\Lambda\pi^0)$ **Γ_7/Γ_1**

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(p\pi^-)/\Gamma(\Lambda\pi^0)$ **Γ_8/Γ_1**

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3.6	90		GEWENIGER	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<180	90	0	YEH	74	HBC	Effective denom.=1300
< 90			DAUBER	69	HBC	
<500			HUBBARD	66	HBC	

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.3			DAUBER 69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.4	90	0	YEH 74	HBC	Effective denom.=670
<6			HUBBARD 66	HBC	

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

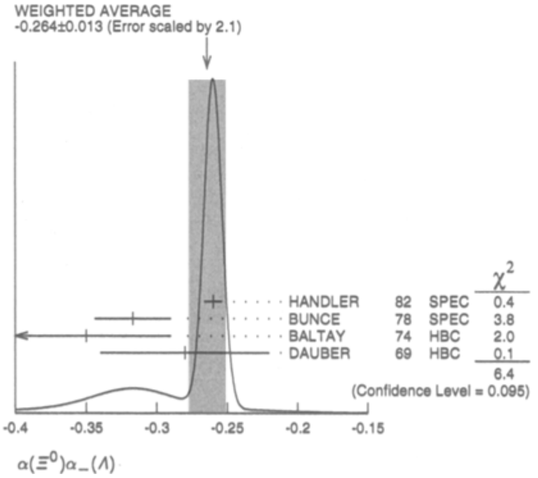
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.3			DAUBER 69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.5	90	0	YEH 74	HBC	Effective denom.=664
<6			HUBBARD 66	HBC	

Ξ^0 DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

$\alpha(\Xi^0)\,\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.264±0.013 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.			
−0.260±0.004±0.005	300k	HANDLER 82	SPEC	FNAL hyperons
−0.317±0.027	6075	BUNCE 78	SPEC	FNAL hyperons
−0.35 ±0.06	505	BALTAY 74	HBC	K^-p 1.75 GeV/c
−0.28 ±0.06	739	DAUBER 69	HBC	K^-p 1.7–2.6 GeV/c



α FOR $\Xi^0 \to \Lambda\pi^0$

The above average, $\alpha(\Xi^0)\alpha_-(\Lambda) = -0.264 \pm 0.013$, where the error includes a scale factor of 2.1, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^0)$.

VALUE	DOCUMENT ID
−0.411±0.022 OUR EVALUATION	Error includes scale factor of 2.1.

ϕ ANGLE FOR $\Xi^0 \to \Lambda\pi^0$ $(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
21±12 OUR AVERAGE				
16±17	652	BALTAY 74	HBC	1.75 GeV/c K^-p
38±19	739	[3] DAUBER 69	HBC	
− 8±30	146	[4] BERGE 66	HBC	

[3] DAUBER 69 uses $\alpha_\Lambda = 0.647 \pm 0.020$.

[4] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

α FOR $\Xi^0 \to \Lambda\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
+0.43±0.44	87	JAMES 90	SPEC	FNAL hyperons

α FOR $\Xi^0 \to \Sigma^0\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
+0.20±0.32±0.05	85	TEIGE 89	SPEC	FNAL hyperons

Ξ^0 REFERENCES

JAMES	90	PRL 64 843	+Heller, Border, Dworkin+	(MINN, MICH, WISC, RUTG)
TEIGE	89	PRL 63 2717	+Beretvas, Caracappa, Devlin+	(RUTG, MICH, MINN)
BENSINGER	88	PL B215 195	+Fortner, Kirsch, Piekarz+	(BRAN, DUKE, NDAM, MASD)
HANDLER	82	PR D25 639	+Grobel, Pondrom+	(WISC, MICH, MINN, RUTG)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
BUNCE	79	PL 86B 386	+Overseth, Cox+	(BNL, MICH, RUTG, WISC)
BUNCE	78	PR D18 633	+Handler, March, Martin+	(WISC, MICH, RUTG)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEIDH)
GEWENIGER	75	PL 57B 193	+Gjesdal, Presser+	(CERN, HEIDH)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFTS, LOUC)
Also	73	NP B53 268 erratum	Mayeur	
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFTS, LOUC)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
HUBBARD	66	Thesis UCRL 11510		(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
JAUNEAU	63	PL 4 49	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63C	Siena Conf. 1 1	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Ξ^- MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements. It assumes the Ξ^- and $\overline{\Xi}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1321.32±0.13 OUR FIT				
1321.34±0.14 OUR AVERAGE				
1321.46±0.34	632	DIBIANCA 75	DBC	4.9 GeV/c K^-d
1321.12±0.41	268	WILQUET 72	HLBC	
1321.87±0.51	195	[1] GOLDWASSER 70	HBC	5.5 GeV/c K^-p
1321.67±0.52	6	CHIEN 66	HBC	6.9 GeV/c $\overline{p}p$
1321.4 ±1.1	299	LONDON 66	HBC	
1321.3 ±0.4	149	PJERROU 65B	HBC	
1321.1 ±0.3	241	[2] BADIER 64	HBC	
1321.4 ±0.4	517	[2] JAUNEAU 63D	FBC	
1321.1 ±0.65	62	[2] SCHNEIDER 63	HBC	

[1] GOLDWASSER 70 uses $m_\Lambda = 1115.58$ MeV.

[2] These masses have been increased 0.09 MeV because the Λ mass increased.

$\overline{\Xi}^+$ MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements. It assumes the Ξ^- and $\overline{\Xi}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1321.32±0.13 OUR FIT				
1321.20±0.33 OUR AVERAGE				
1321.6 ±0.8	35	VOTRUBA 72	HBC	10 GeV/c K^+p
1321.2 ±0.4	34	STONE 70	HBC	
1320.69±0.93	5	CHIEN 66	HBC	6.9 GeV/c $\overline{p}p$

$(m_{\Xi^-} - m_{\overline{\Xi}^+})\,/\,m_{\text{average}}$

A test of *CPT* invariance. We calculate it from the *average* Ξ^- and $\overline{\Xi}^+$ masses above.

VALUE	DOCUMENT ID
$(1.1\pm2.7)\times10^{-4}$ OUR EVALUATION	

Ξ^- MEAN LIFE

Measurements with an error > 0.2×10^{-10} s or with systematic errors not included have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.639±0.015 OUR AVERAGE					
1.652±0.051	32k	BOURQUIN	84	SPEC	Hyperon beam
1.665±0.065	41k	BOURQUIN	79	SPEC	Hyperon beam
1.609±0.028	4286	HEMINGWAY	78	HBC	4.2 GeV/c $K^- p$
1.67 ±0.08		DIBIANCA	75	DBC	4.9 GeV/c $K^- d$
1.63 ±0.03	4303	BALTAY	74	HBC	1.75 GeV/c $K^- p$
$1.73\ ^{+0.08}_{-0.07}$	680	MAYEUR	72	HLBC	2.1 GeV/c K^-
1.61 ±0.04	2610	DAUBER	69	HBC	
1.80 ±0.16	299	LONDON	66	HBC	
1.70 ±0.12	246	PJERROU	65B	HBC	
1.69 ±0.07	794	HUBBARD	64	HBC	
$1.86\ ^{+0.15}_{-0.14}$	517	JAUNEAU	63D	FBC	

$\overline{\Xi}^+$ MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.6 ±0.3	34	STONE	70	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.55\ ^{+0.35}_{-0.20}$	35	[3] VOTRUBA	72	HBC	10 GeV/c $K^+ p$
$1.9\ ^{+0.7}_{-0.5}$	12	[3] SHEN	67	HBC	
1.51±0.55	5	[3] CHIEN	66	HBC	6.9 GeV/c $\overline{p} p$

[3] The error is statistical only.

$(\tau_{\Xi^-} - \tau_{\overline{\Xi}^+}) \,/\, \tau_{\mathrm{average}}$

A test of *CPT* invariance. Calculated from the Ξ^- and $\overline{\Xi}^+$ mean lives, above.

VALUE	DOCUMENT ID
0.02±0.18 OUR EVALUATION	

Ξ^- MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.6507±0.0025 OUR AVERAGE					
−0.6505±0.0025	4.36M	DURYEA	92	SPEC	800 GeV p Be
−0.661 ±0.036 ±0.036	44k	TROST	89	SPEC	Ξ^- ~ 250 GeV
−0.69 ±0.04	218k	RAMEIKA	84	SPEC	400 GeV pBe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.674 ±0.021 ±0.020	122k	HO	90	SPEC	See DURYEA 92
−2.1 ±0.8	2436	COOL	74	OSPK	1.8 GeV/c $K^- p$
−0.1 ±2.1	2724	BINGHAM	70B	OSPK	1.8 GeV/c $K^- p$

$\overline{\Xi}^+$ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
+0.657±0.028±0.020	70k	HO	90	SPEC	800 GeV pBe

Ξ^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^-$		(99.887±0.035) %	
Γ_2	$\Sigma^-\gamma$		(1.27 ±0.23) $\times 10^{-4}$	
Γ_3	$\Lambda e^- \overline{\nu}_e$		(5.63 ±0.31) $\times 10^{-4}$	
Γ_4	$\Lambda \mu^- \overline{\nu}_\mu$		($3.5\ ^{+3.5}_{-2.2}$) $\times 10^{-4}$	
Γ_5	$\Sigma^0 e^- \overline{\nu}_e$		(8.7 ±1.7) $\times 10^{-5}$	
Γ_6	$\Sigma^0 \mu^- \overline{\nu}_\mu$		< 8 $\times 10^{-4}$	90%
Γ_7	$\Xi^0 e^- \overline{\nu}_e$		< 2.3 $\times 10^{-3}$	90%
	$\Delta S = 2$ forbidden (*S2*) modes			
Γ_8	$n\pi^-$	*S2*	< 1.9 $\times 10^{-5}$	90%
Γ_9	$n e^- \overline{\nu}_e$	*S2*	< 3.2 $\times 10^{-3}$	90%
Γ_{10}	$n \mu^- \overline{\nu}_\mu$	*S2*	< 1.5 %	90%
Γ_{11}	$p\pi^-\pi^-$	*S2*	< 4 $\times 10^{-4}$	90%
Γ_{12}	$p\pi^- e^- \overline{\nu}_e$	*S2*	< 4 $\times 10^{-4}$	90%
Γ_{13}	$p\pi^- \mu^- \overline{\nu}_\mu$	*S2*	< 4 $\times 10^{-4}$	90%
Γ_{14}	$p\mu^-\mu^-$	*L*	< 4 $\times 10^{-4}$	90%

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 1.0 for 1 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{\mathrm{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{c|cccc}
x_2 & -6 & & & \\
x_3 & -8 & 0 & & \\
x_4 & -99 & 0 & -1 & \\
x_5 & -5 & 0 & 0 & 0 \\
\hline
 & x_1 & x_2 & x_3 & x_4
\end{array}$$

Ξ^- BRANCHING RATIOS

A number of early results have been omitted.

$\Gamma(\Sigma^-\gamma)/\Gamma(\Lambda\pi^-)$ — Γ_2/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.27±0.24 OUR FIT					
1.27±0.23 OUR AVERAGE					
1.22±0.23±0.06	211	[4] DUBBS	94	E761	Ξ^- 375 GeV
2.27±1.02	9	BIAGI	87B	SPEC	SPS hyperon beam

[4] DUBBS 94 also finds weak evidence that the asymmetry parameter α_γ is positive ($\alpha_\gamma = 1.0 \pm 1.3$).

$\Gamma(\Lambda e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.564±0.031 OUR FIT					
0.564±0.031	2857	BOURQUIN	83	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.30 ±0.13	11	THOMPSON	80	ASPK	Hyperon beam

$\Gamma(\Lambda \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.35\ ^{+0.35}_{-0.22}$ OUR FIT						
0.35±0.35		1	YEH	74	HBC	Effective denom.=2859
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 2.3	90	0	THOMPSON	80	ASPK	Effective denom.=1017
< 1.3			DAUBER	69	HBC	
<12			BERGE	66	HBC	

$\Gamma(\Sigma^0 e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.087±0.017 OUR FIT					
0.087±0.017	154	BOURQUIN	83	SPEC	SPS hyperon beam

$\Gamma(\Sigma^0 \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_6/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.76	90	0	YEH	74	HBC	Effective denom.=3026
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5			BERGE	66	HBC	

$[\Gamma(\Lambda e^- \overline{\nu}_e) + \Gamma(\Sigma^0 e^- \overline{\nu}_e)]/\Gamma(\Lambda\pi^-)$ — $(\Gamma_3+\Gamma_5)/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.651±0.031	3011	[5] BOURQUIN	83	SPEC	SPS hyperon beam
0.68 ±0.22	17	[6] DUCLOS	71	OSPK	

[5] See the separate BOURQUIN 83 values for $\Gamma(\Lambda e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ and $\Gamma(\Sigma^0 e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ above.

[6] DUCLOS 71 cannot distinguish Σ^0's from Λ's. The Cabibbo theory predicts the Σ^0 rate is about a factor 6 smaller than the Λ rate.

$\Gamma(\Xi^0 e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_7/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	YEH	74	HBC	Effective denom.=1000

$\Gamma(n\pi^-)/\Gamma(\Lambda\pi^-)$ — Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.019	90		BIAGI	82B	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	0	YEH	74	HBC	Effective denom.=760
<1.1			DAUBER	69	HBC	
<5.0			FERRO-LUZZI	63	HBC	

$\Gamma(ne^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 3.2	90	0	YEH 74	HBC	Effective denom.=715
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<10	90		BINGHAM 65	RVUE	

$\Gamma(n\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<15.3	90	0	YEH 74	HBC	Effective denom.=150

$\Gamma(p\pi^-\pi^-)/\Gamma(\Lambda\pi^-)$ Γ_{11}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<3.7	90	0	YEH 74	HBC	Effective denom.=6200

$\Gamma(p\pi^-e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ Γ_{12}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<3.7	90	0	YEH 74	HBC	Effective denom.=6200

$\Gamma(p\pi^-\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ Γ_{13}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<3.7	90	0	YEH 74	HBC	Effective denom.=6200

$\Gamma(p\mu^-\mu^-)/\Gamma(\Lambda\pi^-)$ Γ_{14}/Γ_1

A ΔL=2 decay, forbidden by total lepton number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<3.7	90	[7] LITTENBERG 92B	HBC	Uses YEH 74 data

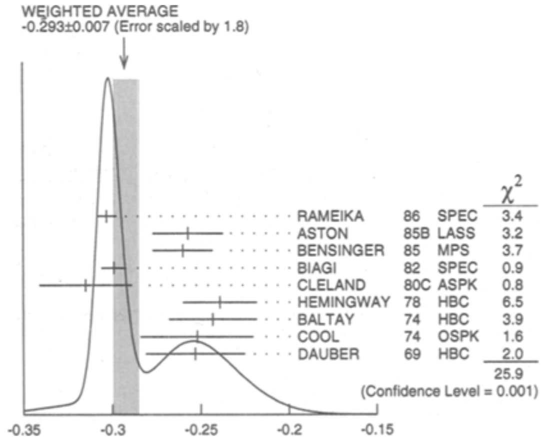
[7] This LITTENBERG 92B limit and the identical YEH 74 limits for the preceding three modes all result from nonobservance of any 3-prong decays of the Ξ^-. One could as well apply the limit to the *sum* of the four modes.

Ξ^- DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

$\alpha(\Xi^-)\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.293±0.007 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.			
−0.303±0.004±0.004	192k	RAMEIKA 86	SPEC	400 GeV pBe
−0.257±0.020	11k	ASTON 85B	LASS	11 GeV/c K^-p
−0.260±0.017	21k	BENSINGER 85	MPS	5 GeV/c K^-p
−0.299±0.007	150k	BIAGI 82	SPEC	SPS hyperon beam
−0.315±0.026	9046	CLELAND 80C	ASPK	BNL hyperon beam
−0.239±0.021	6599	HEMINGWAY 78	HBC	4.2 GeV/c K^-p
−0.243±0.025	4303	BALTAY 74	HBC	1.75 GeV/c K^-p
−0.252±0.032	2436	COOL 74	OSPK	1.8 GeV/c K^-p
−0.253±0.028	2781	DAUBER 69	HBC	



α FOR $\Xi^- \rightarrow \Lambda\pi^-$

The above average, $\alpha(\Xi^-)\,\alpha_-(\Lambda) = -0.293 \pm 0.007$, where the error includes a scale factor of 1.8, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^-)$.

VALUE	DOCUMENT ID
−0.456±0.014 OUR EVALUATION	Error includes scale factor of 1.8.

ϕ ANGLE FOR $\Xi^- \rightarrow \Lambda\pi^-$ $(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
4 ± 4 OUR AVERAGE				
5 ±10	11k	ASTON 85B	LASS	K^-p
14.7±16.0	21k	[8] BENSINGER 85	MPS	5 GeV/c K^-p
11 ± 9	4303	BALTAY 74	HBC	1.75 GeV/c K^-p
5 ±16	2436	COOL 74	OSPK	1.8 GeV/c K^-p
−26 ±30	2724	BINGHAM 70B	OSPK	
−14 ±11	2781	DAUBER 69	HBC	Uses $\alpha_\Lambda = 0.647\pm0.020$
0 ±12	1004	[9] BERGE 66	HBC	
0 ±20.4	364	[9] LONDON 66	HBC	Using $\alpha_\Lambda = 0.62$
54 ±30	356	[9] CARMONY 64B	HBC	

[8] BENSINGER 85 used $\alpha_\Lambda = 0.642 \pm 0.013$.

[9] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

$g_A\,/\,g_V$ FOR $\Xi^- \rightarrow \Lambda e^-\overline{\nu}_e$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.25±0.05	1992	[10] BOURQUIN 83	SPEC	SPS hyperon beam

[10] BOURQUIN 83 assumes that $g_2 = 0$. Also, the sign has been changed to agree with our conventions, given in the "Note on Baryon Decay Parameters" in the neutron Listings.

Ξ^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

DUBBS	94	PRL 72 808	+Albuquerque, Bondar+	(FNAL E761 Collab.)
DURYEA	92	PRL 68 768	+Guglielmo, Heller+	(MINN, FNAL, MICH, RUTG)
LITTENBERG	92B	PR D46 R892	+Shrock	(BNL, STON)
HO	90	PRL 65 1713	+Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
Also	91	PR D44 3402	Ho, Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
TROST	89	PR D40 1703	+McCliment, Newsom, Hseuh, Mueller+	(FNAL-715 Collab.)
BIAGI	87B	ZPHY C35 143	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
RAMEIKA	86	PR D33 3172	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BENSINGER	85	NP B252 561	+	(CHIC, ELMT, FNAL, ISU, PNPI, MASD)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEIDP, LALO, RAL, STRB)
RAMEIKA	84	PRL 52 581	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
BIAGI	82	PL 112B 265	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RL)
BIAGI	82B	PL 112B 277	+	(LOQM, GEVA, RL, HEIDP, CAVE, LAUS, BRIS)
CLELAND	80C	PR D21 12	+Cooper, Dris, Engels, Herbert+	(PITT, BNL)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
BOURQUIN	79	PL 87B 297	+	(BRIS, GEVA, HEIDP, ORSAY, RHEL, STRB)
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
COOL	74	PR D10 792	+Giacomelli, Jenkins, Kycia, Leontic, Li+	(BNL)
Also	72	PRL 29 1630	Cool, Giacomelli, Jenkins, Kycia, Leontic+	(BNL)
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFTS, LOUC)
VOTRUBA	72	NP B45 77	+Safder, Ratcliffe	(BIRM, EDIN)
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFTS, LOUC)
DUCLOS	71	NP B32 493	+Freytag, Heintze, Heinzelmann, Jones+	(CERN)
BINGHAM	70B	PR D1 3010	+Cook, Humphrey, Sander+	(UCSD, WASH)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
STONE	70	PL 32B 515	+Berlinghieri, Bromberg, Cohen, Ferbel+	(ROCH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL) J
SHEN	67	PL 25B 443	+Firestone, Goldhaber	(UCB, LRL)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
BINGHAM	65	PRSL 285 202		(CERN)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
BADIER	64	Dubna Conf. 1 593	+Demoulin, Barloutaud+	(EPOL, SACL, ZEEM)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA) J
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
FERRO-LUZZI	63	PR 130 1568	+Alston-Garnjost, Rosenfeld, Wojcicki	(LRL)
JAUNEAU	63D	Siena Conf. 4	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63B	PL 5 261	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
SCHNEIDER	63	PL 4 360		(CERN)

Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, there has not been a single new piece of data on Ξ resonances since our 1988 edition.

For a detailed earlier review, see Meadows [1].

Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

			Status as seen in —				
Particle	$L_{2I \cdot 2J}$	Overall status	$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	P_{11}	****					Decays weakly
Ξ(1530)	P_{13}	****	****				
Ξ(1620)		*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	D_{13}	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)	1	***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)	1	**					3-body decays
Ξ(2500)		*		*	*		3-body decays

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

Reference

1. B.T. Meadows, in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 283.

Ξ(1530) P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

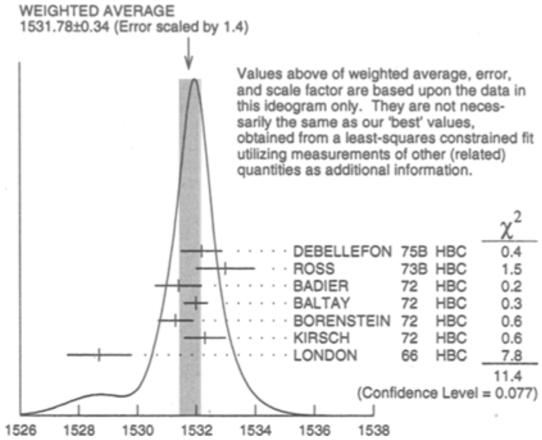
This is the only Ξ resonance whose properties are all reasonably well known. Spin-parity $3/2^+$ is favored by the data.

We use only those determinations of the mass and width that are accompanied by some discussion of systematics and resolution.

Ξ(1530) MASSES

Ξ(1530)^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1531.80±0.32 OUR FIT Error includes scale factor of 1.3.				
1531.78±0.34 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
1532.2 ±0.7		DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1533 ±1		ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
1531.4 ±0.8	59	BADIER 72	HBC	$K^- p$ 3.95 GeV/c
1532.0 ±0.4	1262	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
1531.3 ±0.6	324	BORENSTEIN 72	HBC	$K^- p$ 2.2 GeV/c
1532.3 ±0.7	286	KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
1528.7 ±1.1	76	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1532.1 ±0.4	1244	ASTON 85B	LASS	$K^- p$ 11 GeV/c
1532.1 ±0.6	2700	[1] BAUBILLIER 81B	HBC	$K^- p$ 8.25 GeV/c
1530 ±1	450	BIAGI 81	SPEC	SPS hyperon beam
1527 ±6	80	SIXEL 79	HBC	$K^- p$ 10 GeV/c
1535 ±4	100	SIXEL 79	HBC	$K^- p$ 16 GeV/c
1533.6 ±1.4	97	BERTHON 74	HBC	Quasi-2-body σ



Ξ(1530)$^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1535.0±0.6 OUR FIT				
1535.2±0.8 OUR AVERAGE				
1534.5±1.2		DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1535.3±2.0		ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
1536.2±1.6	185	KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
1535.7±3.2	38	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1540 ±3	48	BERTHON 74	HBC	Quasi-2-body σ
1534.7±1.1	334	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c

$m_{\Xi(1530)^-} - m_{\Xi(1530)}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3.2±0.6 OUR FIT			
2.9±0.9 OUR AVERAGE			
2.7±1.0	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
2.0±3.2	MERRILL 66	HBC	$K^- p$ 1.7–2.7 GeV/c
5.7±3.0	PJERROU 65B	HBC	$K^- p$ 1.8–1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.9±1.8	[2] KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
7 ±4	[2] LONDON 66	HBC	$K^- p$ 2.24 GeV/c

Ξ(1530) WIDTHS

Ξ(1530)^0 WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
9.1±0.5 OUR AVERAGE				
9.5±1.2		DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
9.1±2.4		ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
11 ±2		BADIER 72	HBC	$K^- p$ 3.95 GeV/c
9.0±0.7		BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
8.4±1.4		BORENSTEIN 72	HBC	$\Xi^- \pi^+$
11.0±1.8		KIRSCH 72	HBC	$\Xi^- \pi^+$
7 ±7		BERGE 66	HBC	$K^- p$ 1.5–1.7 GeV/c
8.5±3.5		LONDON 66	HBC	$K^- p$ 2.24 GeV/c
7 ±2		SCHLEIN 63B	HBC	$K^- p$ 1.8, 1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
12.8±1.0	2700	[1] BAUBILLIER 81B	HBC	$K^- p$ 8.25 GeV/c
19 ±6	80	[3] SIXEL 79	HBC	$K^- p$ 10 GeV/c
14 ±5	100	[3] SIXEL 79	HBC	$K^- p$ 16 GeV/c

Ξ(1530)$^-$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$9.9^{+1.7}_{-1.9}$ OUR AVERAGE			
9.6±2.8	DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
8.3±3.6	ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
$7.8^{+3.5}_{-7.8}$	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
16.2±4.6	KIRSCH 72	HBC	$\Xi^- \pi^0$, $\Xi^0 \pi^-$

$\Xi(1530)$ POLE POSITIONS

$\Xi(1530)^0$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1531.6 ± 0.4	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^0$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
4.45 ± 0.35	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1534.4 ± 1.1	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
$3.9^{+1.75}_{-3.9}$	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Xi\pi$	100 %	
Γ_2	$\Xi\gamma$	<4 %	90%

$\Xi(1530)$ BRANCHING RATIOS

$\Gamma(\Xi\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.04	90	KALBFLEISCH 75	HBC	$K^- p$ 2.18 GeV/c

$\Xi(1530)$ FOOTNOTES

[1] BAUBILLIER 81B is a fit to the inclusive spectrum. The resolution (5 MeV) is not unfolded.

[2] Redundant with data in the mass Listings.

[3] SIXEL 79 doesn't unfold the experimental resolution of 15 MeV.

$\Xi(1530)$ REFERENCES

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BAUBILLIER	81B	NP B192 1	+	(BIRM, CERN, GLAS, MSU, CURIN)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
SIXEL	79	NP B159 125	+Bottcher+	(AACH3, BERL, CERN, LOIC, VIEN)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Thesis Nevis 199		(COLU)
ROSS	73B	Purdue Conf. 355	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
BALTAY	72	PL 42B 129	+Bridgewater, Cooper, Gershwin+	(COLU, BING)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
KIRSCH	72	NP B40 349	+Schmidt, Chang+	(BRAN, UMD, SYRA, TUFTS) I
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL) I
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJ
MERRILL	66	Thesis UCRL 16455		(LRL) JP
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
SCHLEIN	63B	PRL 11 167	+Carmony, Pjerrou, Slater, Stork, Ticho	(UCLA) IJP

OTHER RELATED PAPERS

MAZZUCATO	81	NP B178 1	+Pennino+	(AMST, CERN, NIJM, OXF)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFTS)
HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
BUTTON-...	66	PR 142 883	Button-Shafer, Lindsey, Murray, Smith	(LRL) JP

$\Xi(1620)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: *

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

$\Xi(1620)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 1620 OUR ESTIMATE					
1624 ± 3	31	BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
1633 ± 12	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K}\pi$
1606 ± 6	29	ROSS	72	HBC	$K^- p$ 3.1–3.7 GeV/c

$\Xi(1620)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
22.5	31	[1] BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
40 ± 15	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K}\pi$
21 ± 7	29	ROSS	72	HBC	$K^- p \to \Xi^- \pi^+ K^{*0}(892)$

$\Xi(1620)$ DECAY MODES

	Mode
Γ_1	$\Xi\pi$

$\Xi(1620)$ FOOTNOTES

[1] The fit is insensitive to values between 15 and 30 MeV.

$\Xi(1620)$ REFERENCES

HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFTS)
Also	75	PR D12 1859	Briefel, Gourevitch+	(BRAN, UMD, SYRA, TUFTS)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
ROSS	72	PL 38B 177	+Buran, Lloyd, Mulvey, Radojicic	(OXF) I

OTHER RELATED PAPERS

HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
SCHMIDT	73	Purdue Conf. 363		(BRAN)
KALBFLEISCH	70	Duke Conf. 331		(BNL) I
APSELL	69	PRL 23 884	+	(BRAN, UMD, SYRA, TUFTS)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ***

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma\overline{K}$ mass spectra in $K^- p \to (\Sigma\overline{K})K\pi$ at 4.2 GeV/c. The data from the $\Sigma\overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda\overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda\overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0\overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

$\Xi(1690)$ MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
1690 ± 10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\Xi(1690)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1699 ± 5	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
1684 ± 5	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1691.1\pm1.9\pm2.0$	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
1700 ± 10	150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
1694 ± 6	45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
<50 OUR ESTIMATE	

$\Xi(1690)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
44 ± 23	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
20 ± 4	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 8	90	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
47 ± 14		150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
26 ± 6		45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	seen
Γ_3	$\Xi \pi$	
Γ_4	$\Xi^- \pi^+ \pi^0$	
Γ_5	$\Xi^- \pi^+ \pi^-$	possibly seen
Γ_6	$\Xi(1530)\pi$	

$\Xi(1690)$ BRANCHING RATIOS

$\Gamma(\Lambda \overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	104	BIAGI	87	SPEC	–	Ξ^- Be 116 GeV

$\Gamma(\Sigma \overline{K})/\Gamma(\Lambda \overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.7 ± 0.9	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c
3.1 ± 1.4	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi \pi)/\Gamma(\Sigma \overline{K})$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^0)/\Gamma(\Sigma \overline{K})$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	4	BIAGI	87	SPEC	–	Ξ^- Be 116 GeV

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma(\Sigma \overline{K})$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.03	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Sigma \overline{K})$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ FOOTNOTES

[1] From a fit to the $\Sigma^+ K^-$ spectrum.

[2] From a coupled-channel analysis of the $\Sigma^+ K^-$ and $\Lambda \overline{K}^0$ spectra.

[3] A fit to the inclusive spectrum from $\Xi^- N \rightarrow \Lambda K^- X$.

[4] From a coupled-channel analysis of the $\Sigma^0 K^-$ and ΛK^- spectra.

$\Xi(1690)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL) I
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
DIONISI	78	PL 80B 145	+Diaz, Armenteros+	(CERN, AMST, NIJM, OXF) I

$\boxed{\Xi(1820)\ D_{13}}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

The clearest evidence is an 8-standard-deviation peak in ΛK^- seen by GAY 76. TEODORO 78 favors J=3/2, but cannot make a parity discrimination. BIAGI 87C is consistent with J=3/2 and favors negative parity for this J value.

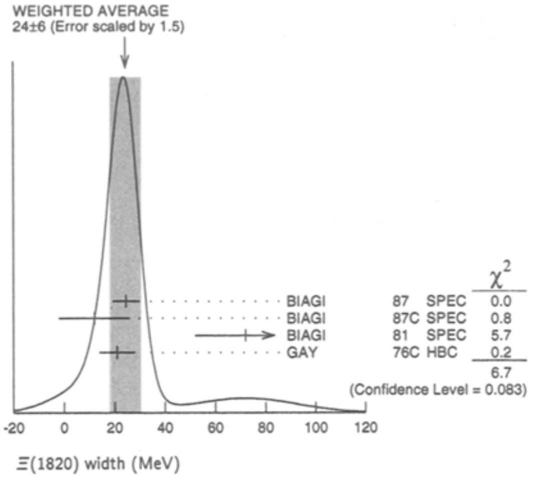
$\Xi(1820)$ MASS

We only average the measurements that appear to us to be most significant and best determined.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1823 ± 5 OUR ESTIMATE						
1823.4 ± 1.4 OUR AVERAGE						
$1819.4 \pm 3.1 \pm 2.0$	280	[1] BIAGI	87	SPEC	0	Ξ^- Be $\rightarrow (\Lambda K^-)$ X
$1826 \pm 3 \pm 1$	54	BIAGI	87C	SPEC	0	Ξ^- Be $\rightarrow (\Lambda \overline{K}^0)$ X
1822 ± 6		JENKINS	83	MPS	–	$K^- p \rightarrow K^+$ (MM)
1830 ± 6	300	BIAGI	81	SPEC	–	SPS hyperon beam
1823 ± 2	130	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1797 ± 19	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
1829 ± 9	68	BRIEFEL	77	HBC	–0	$\Xi(1530)\pi$
1860 ± 14	39	BRIEFEL	77	HBC	–	$\Sigma^- \overline{K}^0$
1870 ± 9	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
1813 ± 4	57	BRIEFEL	77	HBC	–	ΛK^-
1807 ± 27		DIBIANCA	75	DBC	–0	$\Xi \pi \pi$, $\Xi^* \pi$
1762 ± 8	28	[2] BADIER	72	HBC	–0	$\Xi \pi$, $\Xi \pi \pi$, $Y K$
1838 ± 5	38	[2] BADIER	72	HBC	–0	$\Xi \pi$, $\Xi \pi \pi$, $Y K$
1830 ± 10	25	[3] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
1826 ± 12		[4] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
1830 ± 10	40	ALITTI	69	HBC	–	Λ, $\Sigma \overline{K}$
1814 ± 4	30	BADIER	65	HBC	0	$\Lambda \overline{K}^0$
1817 ± 7	29	SMITH	65C	HBC	–0	$\Lambda \overline{K}^0$, ΛK^-
1770		HALSTEINSLID	63	FBC	–0	K^- freon 3.5 GeV/c

$\Xi(1820)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
24^{+15}_{-10} OUR ESTIMATE						
24 ± 6 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.				
24.6 ± 5.3	280	[1] BIAGI	87	SPEC	0	Ξ^- Be $\rightarrow (\Lambda K^-)$ X
$12 \pm 14 \pm 1.7$	54	BIAGI	87C	SPEC	0	Ξ^- Be $\rightarrow (\Lambda \overline{K}^0)$ X
72 ± 20	300	BIAGI	81	SPEC	–	SPS hyperon beam
21 ± 7	130	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
99 ± 57	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
52 ± 34	68	BRIEFEL	77	HBC	–0	$\Xi(1530)\pi$
72 ± 17	39	BRIEFEL	77	HBC	–	$\Sigma^- \overline{K}^0$
44 ± 11	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
26 ± 11	57	BRIEFEL	77	HBC	–	ΛK^-
85 ± 58		DIBIANCA	75	DBC	–0	$\Xi \pi \pi$, $\Xi^* \pi$
51 ± 13		[2] BADIER	72	HBC	–0	Lower mass
58 ± 13		[2] BADIER	72	HBC	–0	Higher mass
103^{+38}_{-24}		[3] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
48^{+36}_{-19}		[4] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
55^{+40}_{-20}		ALITTI	69	HBC	–	Λ, $\Sigma \overline{K}$
12 ± 4		BADIER	65	HBC	0	$\Lambda \overline{K}^0$
30 ± 7		SMITH	65B	HBC	–0	$\Lambda \overline{K}$
< 80		HALSTEINSLID	63	FBC	–0	K^- freon 3.5 GeV/c



$\Xi(1820)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	large
Γ_2	$\Sigma\overline{K}$	small
Γ_3	$\Xi\pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi\pi\pi(\text{not}\,\Xi(1530)\pi)$	

$\Xi(1820)$ BRANCHING RATIOS

The dominant modes seem to be $\Lambda\overline{K}$ and (perhaps) $\Xi(1530)\pi$, but the branching fractions are very poorly determined.

$\Gamma(\Lambda\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.30±0.15	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.10±0.10	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Lambda\overline{K})$ — Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<0.36	95	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
0.20±0.20		BADIER	65	HBC	0	$K^- p$ 3 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ — Γ_3/Γ_4

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$1.5^{+0.6}_{-0.4}$	APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Gamma(\Sigma\overline{K})/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.30±0.15	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	TRIPP	67	RVUE		Use SMITH 65C

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ — Γ_2/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.24±0.10	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.30±0.15	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	ASTON	85B	LASS		$K^- p$ 11 GeV/c
not seen	[5] HASSALL	81	HBC		$K^- p$ 6.5 GeV/c
<0.25	[6] DAUBER	69	HBC		$K^- p$ 2.7 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Lambda\overline{K})$ — Γ_4/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.38±0.27 OUR AVERAGE	Error includes scale factor of 2.3.				
1.0 ±0.3	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
0.26±0.13	SMITH	65C	HBC	–0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi(\text{not}\,\Xi(1530)\pi))/\Gamma(\Lambda\overline{K})$ — Γ_5/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.30±0.20	BIAGI	87	SPEC	–	Ξ^- Be 116 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.14	[7] BADIER	65	HBC	0	1 st. dev. limit
>0.1	SMITH	65C	HBC	–0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi(\text{not}\,\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ — Γ_5/Γ_4

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
consistent with zero	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.3±0.5	[8] APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Xi(1820)$ FOOTNOTES

[1] BIAGI 87 also sees weak signals in the in the $\Xi^-\pi^+\pi^-$ channel at 1782.6 ± 1.4 MeV ($\Gamma = 6.0 \pm 1.5$ MeV) and 1831.9 ± 2.8 MeV ($\Gamma = 9.6 \pm 9.9$ MeV).

[2] BADIER 72 adds all channels and divides the peak into lower and higher mass regions. The data can also be fitted with a single Breit-Wigner of mass 1800 MeV and width 150 MeV.

[3] From a fit to inclusive $\Xi\pi$, $\Xi\pi\pi$, and ΛK^- spectra.

[4] From a fit to inclusive $\Xi\pi$ and $\Xi\pi\pi$ spectra only.

[5] Including $\Xi\pi\pi$.

[6] DAUBER 69 uses in part the same data as SMITH 65C.

[7] For the decay mode $\Xi^-\pi^+\pi^0$ only. This limit includes $\Xi(1530)\pi$.

[8] Or less. Upper limit for the 3-body decay.

$\Xi(1820)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)	
BIAGI	87C	ZPHY C34 175	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)	JP
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)	
JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)	
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)	
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)	
TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)	
Also	69	PRL 23 884	Apsell+	(BRAN, UMD, SYRA, TUFTS)	
GAY	76	NC 31A 593	+Jeanneret, Bogdanski+	(NEUC, LAUS, LIVP, CURIN)	
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)	IJ
DIBIANCA	75	NP B98 137	+Endorf	(CMU)	
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)	
APSELL	70	PRL 24 777	+	(BRAN, UMD, SYRA, TUFTS)	I
CRENNELL	70B	PR D1 847	+Karshon, Lai, O'Neall, Scarr, Schumann	(BNL)	
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA)	I
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)	
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)	
BADIER	65	PL 16 171	+Demoulin, Goldberg+	(EPOL, SACL, AMST)	I
SMITH	65B	Athens Conf. 251	+Lindsey	(LRL)	
SMITH	65C	PRL 14 25	+Lindsey, Button-Shafer, Murray	(LRL)	IJP
HALSTEINSLID	63	Siena Conf. 1 73	+	(BERG, CERN, EPOL, RHEL, LOUC)	I

OTHER RELATED PAPERS

TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFTS)	
SCHMIDT	73	Purdue Conf. 363		(BRAN)	
MERRILL	68	PR 167 1202	+Shafer	(LRL)	
SMITH	64	PRL 13 61	+Lindsey, Murray, Button-Shafer+	(LRL)	IJP

$\boxed{\Xi(1950)}$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

We list here everything reported between 1875 and 2000 MeV. The accumulated evidence for a Ξ near 1950 MeV seems strong enough to include a $\Xi(1950)$ in the main Baryon Table, but not much can be said about its properties. In fact, there may be more than one Ξ near this mass.

$\Xi(1950)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1950±15 OUR ESTIMATE					
1944± 9	129	BIAGI	87	SPEC	Ξ^- Be $\rightarrow (\Xi^-\pi^+)\pi^- X$
1963± 5±2	63	BIAGI	87C	SPEC	Ξ^- Be $\rightarrow (\Lambda\overline{K}^0) X$
1937± 7	150	BIAGI	81	SPEC	SPS hyperon beam
1961±18	139	BRIEFEL	77	HBC	2.87 $K^- p \rightarrow \Xi^-\pi^+ X$
1936±22	44	BRIEFEL	77	HBC	2.87 $K^- p \rightarrow \Xi^0\pi^- X$
1964±10	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
1900±12		DIBIANCA	75	DBC	$\Xi\pi$
1952±11	25	ROSS	73C		$(\Xi\pi)^-$
1956± 6	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, $Y K$
1955±14	21	GOLDWASSER	70	HBC	$\Xi\pi$
1894±18	66	DAUBER	69	HBC	$\Xi\pi$
1930±20	27	ALITTI	68	HBC	$\Xi^-\pi^+$
1933±16	35	BADIER	65	HBC	$\Xi^-\pi^+$

$\Xi(1950)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
60±20 OUR ESTIMATE					
100±31	129	BIAGI	87	SPEC	$\Xi^- \mathrm{Be} \to (\Xi^- \pi^+)\pi^- X$
25±15±1.2	63	BIAGI	87C	SPEC	$\Xi^- \mathrm{Be} \to (\Lambda \overline{K}^0) X$
60± 8	150	BIAGI	81	SPEC	SPS hyperon beam
159±57	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
87±26	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
60±39	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
63±78		DIBIANCA	75	DBC	$\Xi\pi$
38±10		ROSS	73C		$(\Xi\pi)^-$
35±11	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
56±26	21	GOLDWASSER	70	HBC	$\Xi\pi$
98±23	66	DAUBER	69	HBC	$\Xi\pi$
80±40	27	ALITTI	68	HBC	$\Xi^- \pi^+$
140±35	35	BADIER	65	HBC	$\Xi^- \pi^+$

$\Xi(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	possibly seen
Γ_3	$\Xi\pi$	seen
Γ_4	$\Xi(1530)\pi$	
Γ_5	$\Xi\pi\pi$(not $\Xi(1530)\pi$)	

$\Xi(1950)$ BRANCHING RATIOS

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	BIAGI	87C	SPEC	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
possibly seen	17	HASSALL	81	HBC	$K^- p$ 6.5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN
$2.8^{+0.7}_{-0.6}$	APSELL	70	HBC

$\Gamma(\Xi\pi\pi(\text{not}\,\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ Γ_5/Γ_4

VALUE	DOCUMENT ID		TECN
0.0±0.3	APSELL	70	HBC

$\Xi(1950)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
BIAGI	87C	ZPHY C34 175	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFTS)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ROSS	73C	Purdue Conf. 345	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
APSELL	70	PRL 24 777	+	(BRAN, UMD, SYRA, TUFTS)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
ALITTI	68	PRL 21 1119	+Flaminio, Metzger, Radojicic+	(BNL, SYRA)
BADIER	65	PL 16 171	+Demoulin, Goldberg+	(EPOL, SACL, AMST)

$\Xi(2030)$

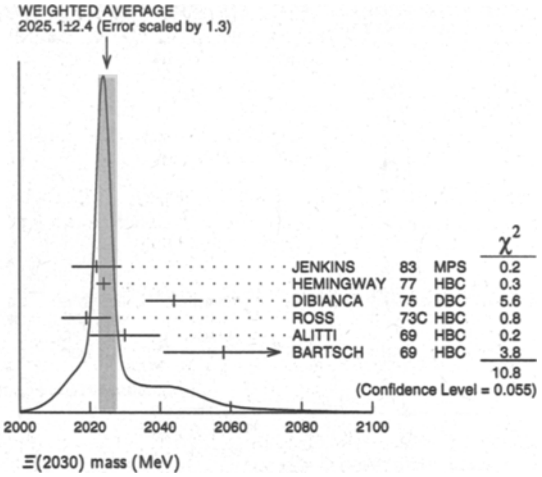
$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$ Status: ∗∗∗

The evidence for this state has been much improved by HEMINGWAY 77, who see an eight standard deviation enhancement in $\Sigma\overline{K}$ and a weaker coupling to $\Lambda\overline{K}$. ALITTI 68 and HEMINGWAY 77 observe no signals in the $\Xi\pi\pi$ (or $\Xi(1530)\pi$) channel, in contrast to DIBIANCA 75. The decay $(\Lambda/\Sigma)\overline{K}\pi$ reported by BARTSCH 69 is also not confirmed by HEMINGWAY 77.

A moments analysis of the HEMINGWAY 77 data indicates at a level of three standard deviations that $J \geq 5/2$.

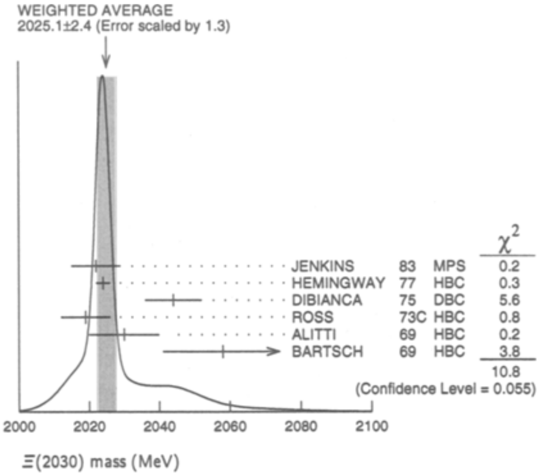
$\Xi(2030)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2025 ± 5 OUR ESTIMATE						
2025.1± 2.4 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
2022 ± 7		JENKINS	83	MPS	–	$K^- p \to K^+$ MM
2024 ± 2	200	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c
2044 ± 8		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
2019 ± 7	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
2030 ±10	42	ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c
2058 ±17	40	BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



$\Xi(2030)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
20^{+15}_{-5} OUR ESTIMATE						
21± 6 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
16± 5	200	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c
60±24		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
33±17	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
45^{+40}_{-20}		ALITTI	69	HBC	–	$K^- p$ 3.9–5 GeV/c
57±30		BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



$\Xi(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	~ 20 %
Γ_2	$\Sigma \overline{K}$	~ 80 %
Γ_3	$\Xi\pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi\pi\pi$(not $\Xi(1530)\pi$)	small
Γ_6	$\Lambda \overline{K}\pi$	small
Γ_7	$\Sigma \overline{K}\pi$	small

$\Xi(2030)$ BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	ALITTI	69	HBC	–	1 standard dev. limit

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.19	95	HEMINGWAY	77	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K})/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.25 ± 0.15	ALITTI	69	HBC	$-$	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Lambda\overline{K})/\Gamma(\Sigma\overline{K})$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22 ± 0.09	HEMINGWAY	77	HBC	$-$	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K})/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75 ± 0.20	ALITTI	69	HBC	$-$	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	ALITTI	69	HBC	$-$	1 standard dev. limit

$[\Gamma(\Xi(1530)\pi)+\Gamma(\Xi\pi\pi(\text{not}\,\Xi(1530)\pi))]/\Gamma(\Sigma\overline{K})$ $(\Gamma_4+\Gamma_5)/\Gamma_2$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.11	95	[1] HEMINGWAY	77	HBC	$-$	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Lambda\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.32	95	HEMINGWAY	77	HBC	$-$	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Sigma\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_7/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	95	[2] HEMINGWAY	77	HBC	$-$	$K^- p$ 4.2 GeV/c

$\Xi(2030)$ FOOTNOTES

[1] For the decay mode $\Xi^-\pi^+\pi^-$ only.

[2] For the decay mode $\Sigma^\pm K^-\pi^\mp$ only.

$\Xi(2030)$ REFERENCES

JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF) IJ
Also	76C	PL 62B 477	Gay, Armenteros, Berge+	(AMST, CERN, NIJM)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ROSS	73C	Purdue Conf. 345	+Lloyd, Radojicic	(OXF)
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA) I
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)
ALITTI	68	PRL 21 1119	+Flaminio, Metzger, Radojicic+	(BNL, SYRA)

$\Xi(2120)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $*$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

$\Xi(2120)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2120 OUR ESTIMATE					
2137 ± 4	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
2123 ± 7		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
25 ± 12		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	seen

$\Xi(2120)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[1] CHLIAPNIK...	79	HBC	$K^+ p \to (\overline{\Lambda} K^+)\,X$
seen	[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ FOOTNOTES

[1] CHLIAPNIKOV 79 does not uniquely identify the K^+ in the $(\overline{\Lambda} K^+)\,X$ final state. It also reports bumps with fewer events at 2240, 2540, and 2830 MeV.

[2] GAY 76C sees a 4-standard deviation signal. However, HEMINGWAY 77, with more events from the same experiment points out that the signal is greatly reduced if a cut is made on the 4-momentum u. This suggests an anomalous production mechanism if the $\Xi(2120)$ is real.

$\Xi(2120)$ REFERENCES

CHLIAPNIK...	79	NP B158 253	Chliapnikov, Gerdyukov+	(CERN, BELG, MONS)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF)
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)

$\Xi(2250)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $**$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The evidence for this state is mixed. BARTSCH 69 sees a bump of not much statistical significance in $\Lambda\overline{K}\pi$, $\Sigma\overline{K}\pi$, and $\Xi\pi\pi$ mass spectra. GOLDWASSER 70 sees a narrower bump in $\Xi\pi\pi$ at a higher mass. Not seen by HASSALL 81 with 45 events/μb at 6.5 GeV/c. Seen by JENKINS 83. Perhaps seen by BIAGI 87.

$\Xi(2250)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2250 OUR ESTIMATE						
2189 ± 7	66	BIAGI	87	SPEC	$-$	$\Xi^-\,\text{Be} \to (\Xi^-\pi^+\pi^-)\,X$
2214 ± 5		JENKINS	83	MPS	$-$	$K^- p \to K^+$ MM
2295 ± 15	18	GOLDWASSER	70	HBC	$-$	$K^- p$ 5.5 GeV/c
2244 ± 52	35	BARTSCH	69	HBC		$K^- p$ 10 GeV/c

$\Xi(2250)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
46 ± 27	66	BIAGI	87	SPEC	$-$	$\Xi^-\,\text{Be} \to (\Xi^-\pi^+\pi^-)\,X$
<30		GOLDWASSER	70	HBC	$-$	$K^- p$ 5.5 GeV/c
130 ± 80		BARTSCH	69	HBC		

$\Xi(2250)$ DECAY MODES

	Mode
Γ_1	$\Xi\pi\pi$
Γ_2	$\Lambda\overline{K}\pi$
Γ_3	$\Sigma\overline{K}\pi$

$\Xi(2250)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\boxed{\Xi(2370)}$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

$\Xi(2370)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
≈ 2370 OUR ESTIMATE					
2356±10		JENKINS 83	MPS	−	$K^- p \rightarrow K^+$ MM
2370	50	HASSALL 81	HBC	−0	$K^- p$ 6.5 GeV/c
2373± 8	94	AMIRZADEH 80	HBC	−0	$K^- p$ 8.25 GeV/c
2392±27		DIBIANCA 75	DBC		$\Xi 2\pi$

$\Xi(2370)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
80	50	HASSALL 81	HBC	−0	$K^- p$ 6.5 GeV/c
80±25	94	AMIRZADEH 80	HBC	−0	$K^- p$ 8.25 GeV/c
75±69		DIBIANCA 75	DBC		$\Xi 2\pi$

$\Xi(2370)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}\pi$ Includes $\Gamma_4 + \Gamma_6$.	seen
Γ_2	$\Sigma\overline{K}\pi$ Includes $\Gamma_5 + \Gamma_6$.	seen
Γ_3	$\Omega^- K$	
Γ_4	$\Lambda\overline{K}^*(892)$	
Γ_5	$\Sigma\overline{K}^*(892)$	
Γ_6	$\Sigma(1385)\overline{K}$	

$\Xi(2370)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
seen	AMIRZADEH 80	HBC	−0	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{\rm total}$ **Γ_2/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
seen	AMIRZADEH 80	HBC	−0	$K^- p$ 8.25 GeV/c

$[\Gamma(\Lambda\overline{K}\pi) + \Gamma(\Sigma\overline{K}\pi)]/\Gamma_{\rm total}$ **$(\Gamma_1+\Gamma_2)/\Gamma$**

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
seen	50	HASSALL 81	HBC	−0	$K^- p$ 6.5 GeV/c

$\Gamma(\Omega^- K)/\Gamma_{\rm total}$ **Γ_3/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.09±0.04	[1] KINSON 80	HBC	−	$K^- p$ 8.25 GeV/c

$[\Gamma(\Lambda\overline{K}^*(892)) + \Gamma(\Sigma\overline{K}^*(892))]/\Gamma_{\rm total}$ **$(\Gamma_4+\Gamma_5)/\Gamma$**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.22±0.13	[1] KINSON 80	HBC	−	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma(1385)\overline{K})/\Gamma_{\rm total}$ **Γ_6/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.12±0.08	[1] KINSON 80	HBC	−	$K^- p$ 8.25 GeV/c

$\Xi(2370)$ FOOTNOTES

[1] KINSON 80 is a reanalysis of AMIRZADEH 80 with 50% more events.

$\Xi(2370)$ REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, MASD)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAVE, MSU)
AMIRZADEH 80 PL 90B 324 + (BIRM, CERN, GLAS, MSU, CURIN) I
KINSON 80 Toronto Conf. 263 + (BIRM, CERN, GLAS, MSU, CURIN) I
DIBIANCA 75 NP B98 137 +Endorf (CMU)

$\boxed{\Xi(2500)}$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The ALITTI 69 peak might be instead the $\Xi(2370)$ or might be neither the $\Xi(2370)$ nor the $\Xi(2500)$.

$\Xi(2500)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
≈ 2500 OUR ESTIMATE					
2505±10		JENKINS 83	MPS	−	$K^- p \rightarrow K^+$ MM
2430±20	30	ALITTI 69	HBC	−	$K^- p$ 4.6–5 GeV/c
2500±10	45	BARTSCH 69	HBC	−0	$K^- p$ 10 GeV/c

$\Xi(2500)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*
150^{+60}_{-40}	ALITTI 69	HBC	−
59±27	BARTSCH 69	HBC	−0

$\Xi(2500)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi\pi$	
Γ_2	$\Lambda\overline{K}$	
Γ_3	$\Sigma\overline{K}$	
Γ_4	$\Xi\pi\pi$	seen
Γ_5	$\Xi(1530)\pi$	
Γ_6	$\Lambda\overline{K}\pi + \Sigma\overline{K}\pi$	seen

$\Xi(2500)$ BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)]$ **$\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.5	ALITTI 69	HBC	1 standard dev. limit

$\Gamma(\Lambda\overline{K})/[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)]$ **$\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*
0.5±0.2	ALITTI 69	HBC	−

$\Gamma(\Sigma\overline{K})/[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)]$ **$\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*
0.5±0.2	ALITTI 69	HBC	−

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)]$ **$\Gamma_5/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$**

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.2	ALITTI 69	HBC	1 standard dev. limit

$\Gamma(\Xi\pi\pi)/\Gamma_{\rm total}$ **Γ_4/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*
seen	BARTSCH 69	HBC	−0

$[\Gamma(\Lambda\overline{K}\pi) + \Gamma(\Sigma\overline{K}\pi)]/\Gamma_{\rm total}$ **Γ_6/Γ**

VALUE	*DOCUMENT ID*	*TECN*	*CHG*
seen	BARTSCH 69	HBC	−0

$\Xi(2500)$ REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, MASD)
ALITTI 69 PRL 22 79 +Barnes, Flaminio, Metzger+ (BNL, SYRA) I
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)

Ω BARYONS
$(S = -3, I = 0)$

$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

The unambiguous discovery in both production and decay was by BARNES 64. The quantum numbers have not actually been measured, but follow from the assignment of the particle to the baryon decuplet. DEUTSCHMANN 78 and BAUBILLIER 78 rule out $J = 1/2$ and find consistency with $J = 3/2$.

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Ω^- MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1672.45±0.29 OUR FIT				
1672.43±0.32 OUR AVERAGE				
1673 ±1	100	HARTOUNI 85	SPEC	80–280 GeV K^0_L C
1673.0 ±0.8	41	BAUBILLIER 78	HBC	8.25 GeV/c $K^- p$
1671.7 ±0.6	27	HEMINGWAY 78	HBC	4.2 GeV/c $K^- p$
1673.4 ±1.7	4	[1] DIBIANCA 75	DBC	4.9 GeV/c $K^- d$
1673.3 ±1.0	3	PALMER 68	HBC	$K^- p$ 4.6, 5 GeV/c
1671.8 ±0.8	3	SCHULTZ 68	HBC	$K^- p$ 5.5 GeV/c
1674.2 ±1.6	5	SCOTTER 68	HBC	$K^- p$ 6 GeV/c
1672.1 ±1.0	1	[2] FRY 55	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1671.43±0.78	13	[3] DEUTSCH... 73	HBC	$K^- p$ 10 GeV/c
1671.9 ±1.2	6	[3] SPETH 69	HBC	See DEUTSCHMANN 73
1673.0 ±8.0	1	ABRAMS 64	HBC	$\to \Xi^- \pi^0$
1670.6 ±1.0	1	[2] FRY 55B	EMUL	
1615	1	[4] EISENBERG 54	EMUL	

[1] DIBIANCA 75 gives a mass for each event. We quote the average.

[2] The FRY 55 and FRY 55B events were identified as Ω^- by ALVAREZ 73. The masses assume decay to ΛK^- at rest. For FRY 55B, decay from an atomic orbit could Doppler shift the K^- energy and the resulting Ω^- mass by several MeV. This shift is negligible for FRY 55 because the Ω decay is approximately perpendicular to its orbital velocity, as is known because the Λ strikes the nucleus (L.Alvarez, private communication 1973). We have calculated the error assuming that the orbital n is 4 or larger.

[3] Excluded from the average; the Ω^- lifetimes measured by the experiments differ significantly from other measurements.

[4] The EISENBERG 54 mass was calculated for decay in flight. ALVAREZ 73 has shown that the Ω interacted with an Ag nucleus to give $K^- \Xi$ Ag.

$\overline{\Omega}^+$ MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1672.45±0.29 OUR FIT				
1672.5 ±0.7 OUR AVERAGE				
1672 ±1	72	HARTOUNI 85	SPEC	80–280 GeV K^0_L C
1673.1 ±1.0	1	FIRESTONE 71B	HBC	12 GeV/c $K^+ d$

$(m_{\Omega^-} - m_{\overline{\Omega}^+}) \,/\, m_{\text{average}}$

A test of CPT invariance. Calculated from the *average* Ω^- and $\overline{\Omega}^+$ masses, above.

VALUE	*DOCUMENT ID*
(0±5) × 10^{-4} OUR EVALUATION	

Ω^- MEAN LIFE

Measurements with an error > 0.1 × 10^{-10} s have been omitted.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.822±0.012 OUR AVERAGE				
0.811±0.037	1096	LUK 88	SPEC	pBe 400 GeV
0.823±0.013	12k	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.822±0.028	2437	BOURQUIN 79B	SPEC	See BOURQUIN 84

Ω^- MAGNETIC MOMENT

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
−2.02 ±0.05 OUR AVERAGE				
−2.024±0.056	235k	WALLACE 95	SPEC	Ω^- 300–550 GeV
−1.94 ±0.17 ±0.14	25k	DIEHL 91	SPEC	Spin-transfer production

Ω^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΛK^-		(67.8±0.7) %	
Γ_2	$\Xi^0 \pi^-$		(23.6±0.7) %	
Γ_3	$\Xi^- \pi^0$		(8.6±0.4) %	
Γ_4	$\Xi^- \pi^+ \pi^-$		$(4.3^{+3.4}_{-1.3}) \times 10^{-4}$	
Γ_5	$\Xi(1530)^0 \pi^-$		$(6.4^{+5.1}_{-2.0}) \times 10^{-4}$	
Γ_6	$\Xi^0 e^- \overline{\nu}_e$		$(5.6\pm2.8) \times 10^{-3}$	
Γ_7	$\Xi^- \gamma$		$< 4.6 \times 10^{-4}$	90%
	$\Delta S = 2$ forbidden ($S2$) modes			
Γ_8	$\Lambda \pi^-$	$S2$	$< 1.9 \times 10^{-4}$	90%

Ω^- BRANCHING RATIOS

The BOURQUIN 84 values (which include results of BOURQUIN 79B, a separate experiment) are much more accurate than any other results, and so the other results have been omitted.

$\Gamma(\Lambda K^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.678±0.007	14k	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.686±0.013	1920	BOURQUIN 79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^0 \pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.236±0.007	1947	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.234±0.013	317	BOURQUIN 79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^- \pi^0)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.086±0.004	759	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.080±0.008	145	BOURQUIN 79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$4.3^{+3.4}_{-1.3}$	4	BOURQUIN 84	SPEC	SPS hyperon beam

$\Gamma(\Xi(1530)^0 \pi^-)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$6.4^{+5.1}_{-2.0}$	4	[5] BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
∼ 20	1	BOURQUIN 79B	SPEC	See BOURQUIN 84

[5] The same 4 events as in the previous mode, with the isospin factor to take into account $\Xi(1530)^0 \to \Xi^0 \pi^0$ decays included.

$\Gamma(\Xi^0 e^- \overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5.6±2.8	14	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •				
∼ 10	3	BOURQUIN 79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^- \gamma)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 4.6	90	0	ALBUQUERQ...94	E761	Ω^- 375 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<22	90	9	BOURQUIN 84	SPEC	SPS hyperon beam
<31	90	0	BOURQUIN 79B	SPEC	See BOURQUIN 84

$\Gamma(\Lambda \pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 1.9	90	0	BOURQUIN 84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<13	90	0	BOURQUIN 79B	SPEC	See BOURQUIN 84

Ω^- DECAY PARAMETERS

α FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.026±0.026 OUR AVERAGE					
−0.034±0.079	1743	LUK	88	SPEC	pBe 400 GeV
−0.025±0.028	12k	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^0\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.09±0.14	1630	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.05±0.21	614	BOURQUIN	84	SPEC	SPS hyperon beam

Ω^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

WALLACE	95	PRL 74 3732	+Border+	(MINN, ARIZ, MICH, FNAL)
ALBUQUERQ...	94	PR D50 R18	Albuquerque, Bondar, Carrigan+	(FNAL E761 Collab.)
DIEHL	91	PRL 67 804	+Teige, Thompson, Zou+	(RUTG, FNAL, MICH, MINN)
LUK	88	PR D38 19	+Beretvas, Deck+	(RUTG, WISC, MICH, MINN)
HARTOUNI	85	PRL 54 628	+Atiya, Holmes, Knapp, Lee+	(COLU, ILL, FNAL)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEIDP, LALO, RAL, STRB)
Also	79	PL 87B 297	Bourquin+	(BRIS, GEVA, HEIDP, ORSAY, RHEL, STRB)
BOURQUIN	79B	PL 88B 192	+	(BRIS, GEVA, HEIDP, LALO, RAL)
BAUBILLIER	78	PL 78B 342	+	(BIRM, CERN, GLAS, MSU, CURIN, PARIN) J
DEUTSCH...	78	PL 73B 96	Deutschmann+	(AACH3, BERL, CERN, INNS, LOIC+) J
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ALVAREZ	73	PR D8 702		(LBL)
DEUTSCH...	73	NP B61 102	Deutschmann, Kaufmann, Besliv+	(ABCLV Collab.)
FIRESTONE	71B	PRL 26 410	+Goldhaber, Lissauer, Sheldon, Trilling	(LRL)
SPETH	69	PL 29B 252	+	(AACH, BERL, CERN, LOIC, VIEN)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
SCHULTZ	68	PR 168 1509	+	(ILL, ANL, NWES, WISC)
SCOTTER	68	PL 26B 474	+	(BIRM, GLAS, LOIC, MUNI, OXF)
ABRAMS	64	PRL 13 670	+Burnstein, Glasser+	(UMD, NRL)
BARNES	64	PRL 12 204	+Connolly, Crennell, Culwick+	(BNL)
FRY	55	PR 97 1189	+Schneps, Swami	(WISC)
FRY	55B	NC 2 346	+Schneps, Swami	(WISC)
EISENBERG	54	PR 96 541		(CORN)

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

$\Omega(2250)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2252± 9 OUR AVERAGE					
2253±13	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
2251± 9±8	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
55±18 OUR AVERAGE					
81±38	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
48±20	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^-\pi^+K^-$	seen
Γ_2	$\Xi(1530)^0K^-$	seen

$\Omega(2250)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0K^-)/\Gamma(\Xi^-\pi^+K^-)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
~ 1.0	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
0.70±0.20	49	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2250)^-$ REFERENCES

ASTON	87B	PL B194 579	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

$\Omega(2380)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2380 OUR ESTIMATE					
2384±9±8	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
26±23	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ DECAY MODES

	Mode
Γ_1	$\Xi^-\pi^+K^-$
Γ_2	$\Xi(1530)^0K^-$
Γ_3	$\Xi^-\overline{K}^*(892)^0$

$\Omega(2380)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0K^-)/\Gamma(\Xi^-\pi^+K^-)$ Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.44	90	9	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Gamma(\Xi^-\overline{K}^*(892)^0)/\Gamma(\Xi^-\pi^+K^-)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.5±0.3	21	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2380)^-$ REFERENCES

BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

$\Omega(2470)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

A peak in the $\Omega^-\pi^+\pi^-$ mass spectrum with a signal significance claimed to be at least 5.5 standard deviations. There is no reason to seriously doubt the existence of this state, but unless the evidence is overwhelming we usually wait for confirmation from a second experiment before elevating peaks to the Summary Table.

$\Omega(2470)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2474±12	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
72±33	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ DECAY MODES

	Mode
Γ_1	$\Omega^-\pi^+\pi^-$

$\Omega(2470)^-$ REFERENCES

ASTON	88G	PL B215 799	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)

CHARMED BARYONS
($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

CHARMED BARYONS

Figure 1 shows the SU(4) multiplets that have as their lowest levels (a) the SU(3) octet that contains the nucleon, and (b) the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only known charmed baryons each contain one charmed quark and thus belong to the second level of an SU(4) multiplet. Figure 2 shows this level for the SU(4) multiplet of Fig. 1(a). The level splits apart into two SU(3) multiplets, a $\overline{\mathbf{3}}$ that contains the $\Lambda_c(2285)$ and the $\Xi_c(2470)$, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly to $\Lambda_c\pi$, and the $\Omega_c(2710)$, which decays weakly. A second Ξ_c remains to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are needed to fill out the full SU(4) multiplets. Furthermore, *every* N or Δ baryon resonance "starts" another SU(4) multiplet, so the woods are full of charmed baryons, most of which no doubt will forever remain undiscovered. The only candidates so far to belong to more massive multiplets are the $\Lambda_c(2593)$ and the $\Lambda_c(2625)$, and perhaps a $\Xi_c(2645)$; see the Listings.

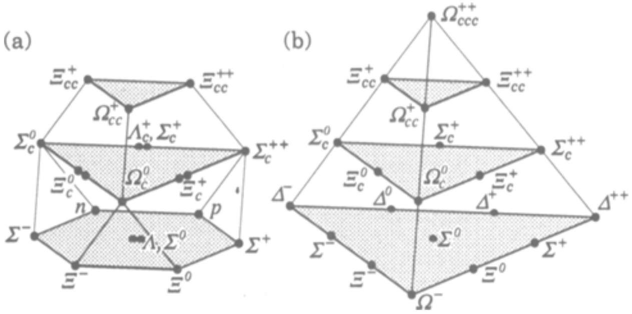


Fig. 1. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet on the lowest level. (b) The 20-plet with an SU(3) decuplet on the lowest level.

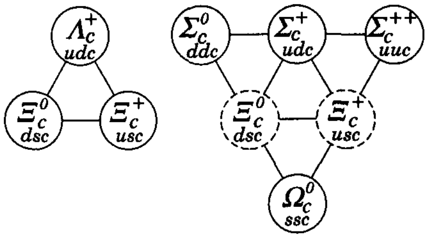


Fig. 2. The SU(3) multiplets on the second level of the SU(4) multiplet of Fig. 1(a). The particles in dashed circles have yet to be discovered.

The states of the $\overline{\mathbf{3}}$ multiplet in Fig. 2 are antisymmetric under interchange of the two light quarks (the u, d, and s quarks), whereas the states of the **6** multiplet are symmetric under interchange of these quarks. Actually, there may be some mixing between the pure $\overline{\mathbf{3}}$ and **6** Ξ_c states (they have the same I, J, and P quantum numbers) to form the physical Ξ_c states.

It need hardly be said that the flavor symmetries Fig. 1 displays are very badly broken, but the figure is the simplest way to see what charmed baryons should exist.

For a review of theory and experiment, see Ref. 1.

References

1. J.G. Körner, M. Krämer, and D. Pirjol, Prog. in Part. Nucl. Phys. **33**, 787 (1994).

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

J has not actually been measured yet. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 92) are consistent with the expected $J = 1/2$. The quark content is udc.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Λ_c^+ MASS

Measurements with an error greater than 5 MeV or that are otherwise obsolete have been omitted.

The fit also includes Σ_c-Λ_c^+ and Λ_c^{*+}-Λ_c^+ mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2284.9±0.6 OUR FIT					
2284.9±0.6 OUR AVERAGE					
2284.7±0.6±0.7	1134	AVERY	91	CLEO	Six modes
2281.7±2.7±2.6	29	ALVAREZ	90B	NA14	$pK^-\pi^+$
2285.8±0.6±1.2	101	BARLAG	89	NA32	$pK^-\pi^+$
2284.7±2.3±0.5	5	AGUILAR-...	88B	LEBC	$pK^-\pi^+$
2283.1±1.7±2.0	628	ALBRECHT	88C	ARG	$pK^-\pi^+$, $p\overline{K}^0$, $\Lambda 3\pi$
2286.2±1.7±0.7	97	ANJOS	88B	E691	$pK^-\pi^+$
2281 ±3	2	JONES	87	HBC	$pK^-\pi^+$
2283 ±3	3	BOSETTI	82	HBC	$pK^-\pi^+$
2290 ±3	1	CALICCHIO	80	HYBR	$pK^-\pi^+$

Λ_c^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-12}$ s or with fewer than 20 events have been omitted.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.206±0.012 OUR AVERAGE					
0.215±0.016±0.008	1340	FRABETTI	93D	E687	γBe, $\Lambda_c^+ \rightarrow pK^-\pi^+$
0.18 ±0.03 ±0.03	29	ALVAREZ	90	NA14	γ, $\Lambda_c^+ \rightarrow pK^-\pi^+$
0.20 ±0.03 ±0.03	90	FRABETTI	90	E687	γBe, $\Lambda_c^+ \rightarrow pK^-\pi^+$
$0.196^{+0.023}_{-0.020}$	101	BARLAG	89	NA32	$pK^-\pi^+$ + c.c.
0.22 ±0.03 ±0.02	97	ANJOS	88B	E691	$pK^-\pi^+$ + c.c.

Λ_c^+ DECAY MODES

Nearly all branching fractions of the Λ_c^+ are measured relative to the $pK^-\pi^+$ mode, but there are no model-independent measurements of this branching fraction. We explain how we arrive at our value of B($\Lambda_c^+ \to pK^-\pi^+$) in a Note at the beginning of the branching-ratio measurements, below. When this branching fraction is eventually well determined, all the other branching fractions will slide up or down proportionally as the true value differs from the value we use here.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes with a p and one $\overline{K}$			
Γ_1	$p\overline{K}^0$		(2.5 ± 0.7) %	
Γ_2	$pK^-\pi^+$	[a]	(5.0 ± 1.3) %	
Γ_3	$p\overline{K}^*(892)^0$	[b]	(1.8 ± 0.6) %	
Γ_4	$\Delta(1232)^{++}K^-$		(8 ± 5) $\times 10^{-3}$	
Γ_5	$\Lambda(1520)\pi^+$	[b]	($4.5\ ^{+2.5}_{-2.1}$) $\times 10^{-3}$	
Γ_6	$pK^-\pi^+$ nonresonant		(2.8 ± 0.9) %	
Γ_7	$p\overline{K}^0\eta$		(1.3 ± 0.4) %	
Γ_8	$p\overline{K}^0\pi^+\pi^-$		(2.4 ± 1.1) %	
Γ_9	$pK^-\pi^+\pi^0$		seen	
Γ_{10}	$pK^*(892)^-\pi^+$	[b]	(1.1 ± 0.6) %	
Γ_{11}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(3.6 ± 1.2) %	
Γ_{12}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{13}	$pK^-\pi^+\pi^+\pi^-$		(1.1 ± 0.8) $\times 10^{-3}$	
Γ_{14}	$pK^-\pi^+\pi^0\pi^0$		(8 ± 4) $\times 10^{-3}$	
Γ_{15}	$pK^-\pi^+\pi^0\pi^0\pi^0$		(5.0 ± 3.4) $\times 10^{-3}$	
	Hadronic modes with a p and zero or two K's			
Γ_{16}	$p\pi^+\pi^-$		(3.5 ± 2.0) $\times 10^{-3}$	
Γ_{17}	$pf_0(980)$	[b]	(2.8 ± 1.9) $\times 10^{-3}$	
Γ_{18}	$p\pi^+\pi^+\pi^-\pi^-$		(1.8 ± 1.2) $\times 10^{-3}$	
Γ_{19}	pK^+K^-		(2.3 ± 0.9) $\times 10^{-3}$	
Γ_{20}	$p\phi$	[b]	(1.2 ± 0.5) $\times 10^{-3}$	
	Hadronic modes with a hyperon			
Γ_{21}	$\Lambda\pi^+$		(9.0 ± 2.8) $\times 10^{-3}$	
Γ_{22}	$\Lambda\pi^+\pi^0$		(3.6 ± 1.3) %	
Γ_{23}	$\Lambda\rho^+$		< 5 %	CL=95%
Γ_{24}	$\Lambda\pi^+\pi^+\pi^-$		(3.3 ± 1.0) %	
Γ_{25}	$\Lambda\pi^+\eta$		(1.7 ± 0.6) %	
Γ_{26}	$\Sigma(1385)^+\eta$	[b]	(8.5 ± 3.3) $\times 10^{-3}$	
Γ_{27}	$\Lambda K^+\overline{K}^0$		(6.0 ± 2.1) $\times 10^{-3}$	
Γ_{28}	$\Sigma^0\pi^+$		(9.9 ± 3.2) $\times 10^{-3}$	
Γ_{29}	$\Sigma^+\pi^0$		(1.00 ± 0.34) %	
Γ_{30}	$\Sigma^+\eta$		(5.5 ± 2.3) $\times 10^{-3}$	
Γ_{31}	$\Sigma^+\pi^+\pi^-$		(3.4 ± 1.0) %	
Γ_{32}	$\Sigma^+\rho^0$		< 1.4 %	CL=95%
Γ_{33}	$\Sigma^-\pi^+\pi^+$		(1.8 ± 0.8) %	
Γ_{34}	$\Sigma^0\pi^+\pi^0$		(1.8 ± 0.8) %	
Γ_{35}	$\Sigma^0\pi^+\pi^+\pi^-$		(1.1 ± 0.4) %	
Γ_{36}	$\Sigma^+\pi^+\pi^-\pi^0$		—	
Γ_{37}	$\Sigma^+\omega$	[b]	(2.7 ± 1.0) %	
Γ_{38}	$\Sigma^+\pi^+\pi^+\pi^-\pi^-$		($3.0\ ^{+4.1}_{-2.1}$) $\times 10^{-3}$	
Γ_{39}	$\Sigma^+K^+K^-$		(3.5 ± 1.2) $\times 10^{-3}$	
Γ_{40}	$\Sigma^+\phi$	[b]	(3.5 ± 1.7) $\times 10^{-3}$	
Γ_{41}	$\Sigma^+K^+\pi^-$		($7\ ^{+6}_{-4}$) $\times 10^{-3}$	
Γ_{42}	Ξ^0K^+		(3.9 ± 1.4) $\times 10^{-3}$	
Γ_{43}	$\Xi^-K^+\pi^+$		(4.9 ± 1.7) $\times 10^{-3}$	
Γ_{44}	$\Xi(1530)^0K^+$	[b]	(2.6 ± 1.0) $\times 10^{-3}$	
	Semileptonic modes			
Γ_{45}	$\Lambda\ell^+\nu_\ell$	[c]	(2.0 ± 0.6) %	
Γ_{46}	$\Lambda e^+\nu_e$		(2.1 ± 0.6) %	
Γ_{47}	$\Lambda\mu^+\nu_\mu$		(2.0 ± 0.7) %	
Γ_{48}	e^+ anything		(4.5 ± 1.7) %	
Γ_{49}	pe^+ anything		(1.8 ± 0.9) %	
Γ_{50}	Λe^+ anything		—	
Γ_{51}	$\Lambda\mu^+$ anything		—	
Γ_{52}	$\Lambda\ell^+\nu_\ell$ anything		—	
	Inclusive modes			
Γ_{53}	p anything		(50 ±16) %	
Γ_{54}	p anything (no Λ)		(12 ±19) %	
Γ_{55}	p hadrons		—	
Γ_{56}	n anything		(50 ±16) %	
Γ_{57}	n anything (no Λ)		(29 ±17) %	
Γ_{58}	Λ anything		(35 ±11) %	S=1.4
Γ_{59}	$\Sigma^\pm$anything	[d]	(10 ± 5) %	
	$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes			
Γ_{60}	$p\mu^+\mu^-$	$C1$	< 3.4 $\times 10^{-4}$	CL=90%
Γ_{61}	$\Sigma^-\mu^+\mu^+$	L	< 7.0 $\times 10^{-4}$	CL=90%

[a] See the "Note on Λ_c^+ Branching Fractions" below.

[b] This branching fraction includes all the decay modes of the final-state resonance.

[c] An ℓ indicates an e or a μ mode, not a sum over these modes.

[d] The value is for the sum of the charge states of particle/antiparticle states indicated.

NOTE ON Λ_c^+ BRANCHING FRACTIONS

Written 1998 by P.R. Burchat (Stanford University).

Most Λ_c^+ branching fractions are measured relative to the decay mode $\Lambda_c^+ \to pK^-\pi^+$. However, there are no model-independent measurements of the absolute branching fraction for $\Lambda_c^+ \to pK^-\pi^+$. Here, we describe the measurements that have been used to extract B($\Lambda_c^+ \to pK^-\pi^+$), the model-dependence of the results, and the method we have used to average the results.

ARGUS (ALBRECHT 88C) and CLEO (CRAWFORD 92) measure B($\overline{B} \to \Lambda_c^+$X) × B($\Lambda_c^+ \to pK^-\pi^+$) to be $(0.30 \pm 0.12 \pm 0.06)\%$ and $(0.273 \pm 0.051 \pm 0.039)\%$. Under the assumptions that decays of $\overline{B}$ mesons to baryons are dominated by $\overline{B} \to \Lambda_c^+$X and that Λ_c^+X final states other than $\Lambda_c^+\overline{N}$X can be neglected, they also measure B($\overline{B} \to \Lambda_c^+$X) to be $(6.8 \pm 0.5 \pm 0.3)\%$ (ALBRECHT 92O) and $(6.4 \pm 0.8 \pm 0.8)\%$ (CRAWFORD 92). Combining these results, we get B($\Lambda_c^+ \to pK^-\pi^+$) = $(4.14 \pm 0.91)\%$. However, the assumption that $\overline{B}$ decay modes to baryons other than $\Lambda_c^+\overline{N}$X are negligible is not on solid ground experimentally or theoretically. Therefore, the branching fraction for $\Lambda_c^+ \to pK^-\pi^+$ given above may be low by some undetermined amount.

The second type of model-dependent determination of B($\Lambda_c^+ \to pK^-\pi^+$) is based on measurements by ARGUS (ALBRECHT 91G) and CLEO (BERGFELD 94) of $\sigma(e^+e^- \to \Lambda_c^+\text{X})\cdot\text{B}(\Lambda_c^+ \to \Lambda\ell^+\nu_\ell) = (4.15 \pm 1.03 \pm 1.18)$ pb and $(4.77 \pm 0.25 \pm 0.66)$ pb. ARGUS (ALBRECHT 96E) and CLEO (AVERY 91) have also measured $\sigma(e^+e^- \to \Lambda_c^+\text{X}) \cdot \text{B}(\Lambda_c^+ \to pK^-\pi^+)$. The weighted average is (11.2 ± 1.3) pb.

From these measurements, we extract $R \equiv \text{B}(\Lambda_c^+ \to pK^-\pi^+)/\text{B}(\Lambda_c^+ \to \Lambda\ell^+\nu_\ell) = 2.40 \pm 0.43$. We estimate the $\Lambda_c^+ \to pK^-\pi^+$ branching fraction from the equation

$$\text{B}(\Lambda_c^+ \to pK^-\pi^+) = R\,f\,F\frac{\Gamma(D \to \text{X}\ell^+\nu_\ell)}{1 + |V_{cd}/V_{cs}|^2}\cdot\tau(\Lambda_c^+) \ , \qquad (1)$$

where $f = \text{B}(\Lambda_c^+ \to \Lambda\ell^+\nu_\ell)/\text{B}(\Lambda_c^+ \to X_s\ell^+\nu_\ell)$ and $F = \Gamma(\Lambda_c^+ \to X_s\ell^+\nu_\ell)/\Gamma(D^0 \to X_s\ell^+\nu_\ell)$. When we use

$1+|V_{cd}/V_{cs}|^2 = 1.05$ and the world averages $\Gamma(D \rightarrow X\ell^+\nu_\ell) = (0.163\pm0.006)\times10^{-12}\ \mathrm{s}^{-1}$ and $\tau(\Lambda_c^+) = (0.206\pm0.012)\times10^{-12}$ s, we calculate $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (7.7\pm1.5)\%\cdot f\,F$. Theoretical estimates for f and F are near 1.0 with significant uncertainties.

So, we have two results with significant model-dependence: $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (4.14\pm0.91)\%$ from $\overline{B}$ decays, and $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (7.7 \pm 1.5)\% \cdot f\,F$ from semileptonic Λ_c^+ decays. If we set $f\,F = 1.0$ in the second result, and assign an uncertainty of 30% to each result to account for the unknown model-dependence, we get the consistent results $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (4.14 \pm 0.91 \pm 1.24)\%$ and $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (7.7 \pm 1.5 \pm 2.3)\%$. The weighted average of these two results is $\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (5.0 \pm 1.3)\%$, where the uncertainty contains both the experimental uncertainty and the 30% estimate of model dependence in each result.

This procedure is clearly rather arbitrary, but so is any other procedure until good measurements of the absolute branching fraction are made. Therefore, we have assigned the value $(5.0 \pm 1.3)\%$ to the $\Lambda_c^+ \rightarrow pK^-\pi^+$ branching fraction (given as PDG 98 below). As was noted earlier, most of the other modes are measured relative to this mode.

Λ_c^+ BRANCHING RATIOS

——— Hadronic modes with a p and one $\overline{K}$ ———

$\Gamma(p\overline{K}^0)/\Gamma(pK^-\pi^+)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.07 OUR AVERAGE					
0.44±0.07±0.05	133	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.55±0.17±0.14	45	ANJOS	90	E691	γBe 70–260 GeV
0.62±0.15±0.03	73	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(pK^-\pi^+)/\Gamma_{\rm total}$ — Γ_2/Γ

See the "Note on Λ_c^+ Branching Fractions" above.

VALUE	DOCUMENT ID		TECN	COMMENT
0.050±0.013	PDG	98		See note at top of ratios
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.041±0.010	[1,2] ALBRECHT	92O	ARG	$e^+e^- \approx \Upsilon(4S)$
0.044±0.012	[1,3] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[1] To extract $\Gamma(pK^-\pi^+)/\Gamma_{\rm total}$, we use $\mathrm{B}(\overline{B} \rightarrow \Lambda_c^+ X)\cdot\mathrm{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (0.28 \pm 0.06)\%$, which is the average of measurements from ARGUS (ALBRECHT 88C) and CLEO (CRAWFORD 92).

[2] ALBRECHT 92O measures $\mathrm{B}(\overline{B} \rightarrow \Lambda_c^+ X) = (6.8 \pm 0.5 \pm 0.3)\%$.

[3] CRAWFORD 92 measures $\mathrm{B}(\overline{B} \rightarrow \Lambda_c^+ X) = (6.4 \pm 0.8 \pm 0.8)\%$.

$\Gamma(p\overline{K}^*(892)^0)/\Gamma(pK^-\pi^+)$ — Γ_3/Γ_2

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.36^{+0.06}_{-0.07}$ OUR AVERAGE					
$0.35^{+0.06}_{-0.07}\pm0.03$	39	BOZEK	93	NA32	π^- Cu 230 GeV
0.42±0.24	12	BASILE	81B	CNTR	$pp \rightarrow \Lambda_c^+ e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.35±0.11		BARLAG	90D	NA32	See BOZEK 93

$\Gamma(\Delta(1232)^{++}K^-)/\Gamma(pK^-\pi^+)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.16±0.10 OUR AVERAGE	Error includes scale factor of 1.5.				
$0.12^{+0.04}_{-0.05}\pm0.05$	14	BOZEK	93	NA32	π^- Cu 230 GeV
0.40±0.17	17	BASILE	81B	CNTR	$pp \rightarrow \Lambda_c^+ e^- X$

$\Gamma(\Lambda(1520)\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_5/Γ_2

Unseen decay modes of the $\Lambda(1520)$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.09^{+0.04}_{-0.03}\pm0.02$	12	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(pK^-\pi^+\ \text{nonresonant})/\Gamma(pK^-\pi^+)$ — Γ_6/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.56^{+0.07}_{-0.09}\pm0.05$	71	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_8/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.17 OUR AVERAGE	Error includes scale factor of 1.4.				
0.43±0.12±0.04	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.98±0.36±0.08	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	44	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^*(892)^-\pi^+)/\Gamma(p\overline{K}^0\pi^+\pi^-)$ — Γ_{10}/Γ_8

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.14	17	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(p(K^-\pi^+)_{\rm nonresonant}\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.73±0.12±0.05	67	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(\Delta(1232)\overline{K}^*(892))/\Gamma_{\rm total}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	35	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^-\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{13}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.015	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{14}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.16±0.07±0.03	15	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(pK^-\pi^+\pi^0\pi^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{15}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.10±0.06±0.02	8	BOZEK	93	NA32	π^- Cu 230 GeV

——— Hadronic modes with a p and 0 or 2 K's ———

$\Gamma(p\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{16}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.069±0.036	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pf_0(980))/\Gamma(pK^-\pi^+)$ — Γ_{17}/Γ_2

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.055±0.036	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\pi^+\pi^+\pi^-\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{18}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.036±0.023	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^+K^-)/\Gamma(pK^-\pi^+)$ — Γ_{19}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.046±0.012 OUR AVERAGE	Error includes scale factor of 1.2.				
0.039±0.009±0.007	214	ALEXANDER	96C	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.096±0.029±0.010	30	FRABETTI	93H	E687	γBe, $\overline{E}_\gamma$ 220 GeV
0.048±0.027		BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\phi)/\Gamma(pK^-\pi^+)$ — Γ_{20}/Γ_2

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.024±0.006±0.003	54	ALEXANDER	96C	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.040±0.027		BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\phi)/\Gamma(pK^+K^-)$ — Γ_{20}/Γ_{19}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.58	90	FRABETTI	93H	E687	γBe, $\overline{E}_\gamma$ 220 GeV

Hadronic modes with a hyperon

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{21}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.180±0.032 OUR AVERAGE					
0.18 ±0.03 ±0.04			ALBRECHT 92	ARG	$e^+e^- \approx 10.4$ GeV
0.18 ±0.03 ±0.03		87	AVERY 91	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.33	90		ANJOS 90	E691	γBe 70–260 GeV
<0.16	90		ALBRECHT 88C	ARG	e^+e^- 10 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ Γ_{22}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.73±0.09±0.16	464	AVERY 94	CLE2	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Lambda\rho^+)/\Gamma(pK^-\pi^+)$ Γ_{23}/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.95	95	AVERY 94	CLE2	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.028±0.007±0.011	70	[4] BOWCOCK 85	CLEO	e^+e^- 10.5 GeV

[4] See BOWCOCK 85 for assumptions made on charm production and Λ_c production from charm to get this result.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{24}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.66±0.11 OUR AVERAGE				
0.65±0.11±0.12	289	AVERY 91	CLEO	e^+e^- 10.5 GeV
0.82±0.29±0.27	44	ANJOS 90	E691	γBe 70–260 GeV
0.94±0.41±0.13	10	BARLAG 90D	NA32	π^- 230 GeV
0.61±0.16±0.04	105	ALBRECHT 88C	ARG	e^+e^- 10 GeV

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(\Lambda\pi^+\pi^+\pi^-)$ Γ_8/Γ_{24}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6±1.2		ALEEV 96	SPEC	n nucleus, 50 GeV/c
4.3±1.2	130	ALEEV 84	BIS2	nC 40–70 GeV

$\Gamma(\Lambda\pi^+\eta)/\Gamma(pK^-\pi^+)$ Γ_{25}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.35±0.05±0.06	116	AMMAR 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma(1385)^+\eta)/\Gamma(pK^-\pi^+)$ Γ_{26}/Γ_2

Unseen decay modes of the $\Sigma(1385)^+$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.17±0.04±0.03	54	AMMAR 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda K^+\overline{K}^0)/\Gamma(pK^-\pi^+)$ Γ_{27}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.12 ±0.02 ±0.02	59	AMMAR 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^0\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{28}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.20±0.04 OUR AVERAGE				
0.21±0.02±0.04	196	AVERY 94	CLE2	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$
0.17±0.06±0.04		ALBRECHT 92	ARG	$e^+e^- \approx 10.4$ GeV

$\Gamma(\Sigma^+\pi^0)/\Gamma(pK^-\pi^+)$ Γ_{29}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.20±0.03±0.03	93	KUBOTA 93	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\eta)/\Gamma(pK^-\pi^+)$ Γ_{30}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.11±0.03±0.02	26	AMMAR 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{31}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.68±0.09 OUR AVERAGE				
0.74±0.07±0.09	487	KUBOTA 93	CLE2	$e^+e^- \approx \Upsilon(4S)$
$0.54^{+0.18}_{-0.15}$	11	BARLAG 92	NA32	π^- Cu 230 GeV

$\Gamma(\Sigma^+\rho^0)/\Gamma(pK^-\pi^+)$ Γ_{32}/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.27	95	KUBOTA 93	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^-\pi^+\pi^+)/\Gamma(\Sigma^+\pi^+\pi^-)$ Γ_{33}/Γ_{31}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.53±0.15±0.07	56	FRABETTI 94E	E687	γBe, $\overline{E}_\gamma$ 220 GeV

$\Gamma(\Sigma^0\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ Γ_{34}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.36±0.09±0.10	117	AVERY 94	CLE2	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Sigma^0\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{35}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.21±0.05±0.05	90	AVERY 94	CLE2	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Sigma^+\omega)/\Gamma(pK^-\pi^+)$ Γ_{37}/Γ_2

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.54±0.13±0.06	107	KUBOTA 93	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{38}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.06^{+0.08}_{-0.04}}$	1	BARLAG 92	NA32	π^- Cu 230 GeV

$\Gamma(\Sigma^+K^+K^-)/\Gamma(pK^-\pi^+)$ Γ_{39}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.070±0.011±0.011	59	AVERY 93	CLE2	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Sigma^+\phi)/\Gamma(pK^-\pi^+)$ Γ_{40}/Γ_2

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.069±0.023±0.016	26	AVERY 93	CLE2	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Sigma^+K^+\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{41}/Γ_2

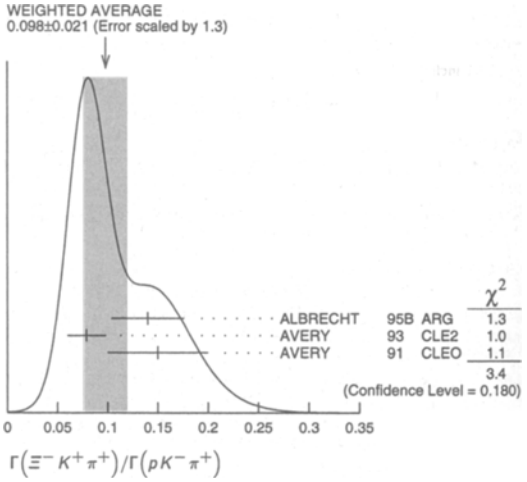
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.13^{+0.12}_{-0.07}}$	2	BARLAG 92	NA32	π^- Cu 230 GeV

$\Gamma(\Xi^0K^+)/\Gamma(pK^-\pi^+)$ Γ_{42}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.078±0.013±0.013	56	AVERY 93	CLE2	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Xi^-K^+\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{43}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.098±0.021 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
0.14 ±0.03 ±0.02	34	ALBRECHT 95B	ARG	$e^+e^- \approx 10.4$ GeV
0.079±0.013±0.014	60	AVERY 93	CLE2	$e^+e^- \approx 10.5$ GeV
0.15 ±0.04 ±0.03	30	AVERY 91	CLEO	e^+e^- 10.5 GeV



$\Gamma(\Xi(1530)^0K^+)/\Gamma(pK^-\pi^+)$ Γ_{44}/Γ_2

Unseen decay modes of the $\Xi(1530)^0$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.052±0.014 OUR AVERAGE				
0.05 ±0.02 ±0.01	11	ALBRECHT 95B	ARG	$e^+e^- \approx 10.4$ GeV
0.053±0.016±0.010	24	AVERY 93	CLE2	$e^+e^- \approx 10.5$ GeV

Semileptonic modes

$\Gamma(\Lambda\ell^+\nu_\ell)/\Gamma(pK^-\pi^+)$ Γ_{45}/Γ_2

VALUE	DOCUMENT ID	COMMENT
0.41±0.05 OUR AVERAGE		
0.42±0.07	PDG 98	Our $\Gamma(\Lambda e^+\nu_e)/\Gamma(pK^-\pi^+)$
0.39±0.08	PDG 98	Our $\Gamma(\Lambda\mu^+\nu_\mu)/\Gamma(pK^-\pi^+)$

$\Gamma(\Lambda e^+\nu_e)/\Gamma(pK^-\pi^+)$ Γ_{46}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.42±0.07 OUR AVERAGE				
0.43±0.08	[5,6] BERGFELD	94	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.38±0.14	[6,7] ALBRECHT	91G	ARG	$e^+e^- \approx$ 10.4 GeV

[5] BERGFELD 94 measures $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c^+ \to \Lambda e^+\nu_e) = (4.87 \pm 0.28 \pm 0.69)$ pb.

[6] To extract $\Gamma(\Lambda_c^+ \to \Lambda e^+\nu_e)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$, we use $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c \to pK^-\pi^+) = (11.2 \pm 1.3)$ pb, which is the weighted average of measurements from ARGUS (ALBRECHT 96E) and CLEO (AVERY 91).

[7] ALBRECHT 91G measures $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c^+ \to \Lambda e^+\nu_e) = (4.20 \pm 1.28 \pm 0.71)$ pb.

$\Gamma(\Lambda\mu^+\nu_\mu)/\Gamma(pK^-\pi^+)$ Γ_{47}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.39±0.08 OUR AVERAGE				
0.40±0.09	[8,9] BERGFELD	94	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.35±0.20	[9,10] ALBRECHT	91G	ARG	$e^+e^- \approx$ 10.4 GeV

[8] BERGFELD 94 measures $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (4.43 \pm 0.51 \pm 0.64)$ pb.

[9] To extract $\Gamma(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$, we use $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c \to pK^-\pi^+) = (11.2 \pm 1.3)$ pb, which is the weighted average of measurements from ARGUS (ALBRECHT 96E) and CLEO (AVERY 91).

[10] ALBRECHT 91G measures $\sigma(e^+e^- \to \Lambda_c^+ X)\cdot B(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.91 \pm 2.02 \pm 0.90)$ pb.

$\Gamma(e^+\text{anything})/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.045±0.017	VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

$\Gamma(pe^+\text{anything})/\Gamma_{\text{total}}$ Γ_{49}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.018±0.009	[11] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

[11] VELLA 82 includes protons from Λ decay.

$\Gamma(\Lambda e^+\text{anything})/\Gamma_{\text{total}}$ Γ_{50}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.011±0.008	[12] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

[12] VELLA 82 includes Λ's from Σ^0 decay.

Inclusive modes

$\Gamma(p\text{ anything})/\Gamma_{\text{total}}$ Γ_{53}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.08±0.14	[13] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[13] This CRAWFORD 92 value includes protons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.

$\Gamma(p\text{ anything (no }\Lambda))/\Gamma_{\text{total}}$ Γ_{54}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.10±0.16	CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

$\Gamma(n\text{ anything})/\Gamma_{\text{total}}$ Γ_{56}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.08±0.14	[14] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[14] This CRAWFORD 92 value includes neutrons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.

$\Gamma(n\text{ anything (no }\Lambda))/\Gamma_{\text{total}}$ Γ_{57}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.29±0.09±0.15	CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

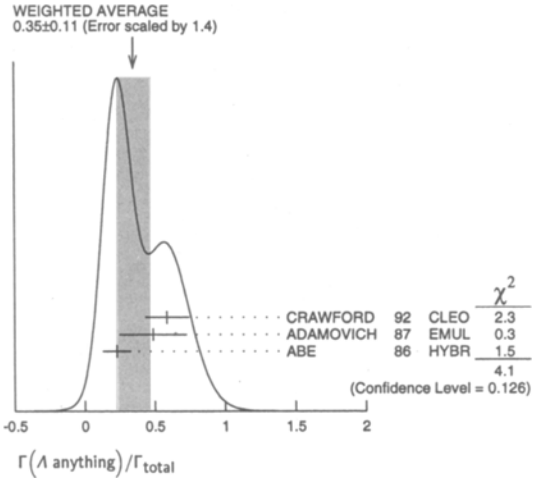
$\Gamma(p\text{ hadrons})/\Gamma_{\text{total}}$ Γ_{55}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41±0.24	ADAMOVICH	87	EMUL	γA 20–70 GeV/c

$\Gamma(\Lambda\text{ anything})/\Gamma_{\text{total}}$ Γ_{58}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.11 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
0.59±0.10±0.12		CRAWFORD	92	CLEO	e^+e^- 10.5 GeV
0.49±0.24		ADAMOVICH	87	EMUL	γA 20–70 GeV/c
0.23±0.10	8	[15] ABE	86	HYBR	20 GeV γp

[15] ABE 86 includes Λ's from Σ^0 decay.



$\Gamma(\Sigma^\pm\text{anything})/\Gamma_{\text{total}}$ Γ_{59}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1 ±0.05	5	ABE	86	HYBR	20 GeV γp

Rare or forbidden modes

$\Gamma(p\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{60}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(\Sigma^-\mu^+\mu^+)/\Gamma_{\text{total}}$ Γ_{61}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<7.0 \times 10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

Λ_c^+ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

α FOR $\Lambda_c^+ \to \Lambda\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.98±0.19 OUR AVERAGE					
−0.94±0.21±0.12	414	[16] BISHAI	95	CLE2	$e^+e^- \approx \Upsilon(4S)$
−0.96±0.42		ALBRECHT	92	ARG	$e^+e^- \approx$ 10.4 GeV
−1.1 ±0.4	86	AVERY	90B	CLEO	$e^+e^- \approx$ 10.6 GeV

[16] BISHAI 95 actually gives $\alpha = -0.94^{+0.21}_{-0.06}{}^{+0.12}_{-0.06}$, chopping the errors at the physical limit −1.0. However, for $\alpha \approx -1.0$, some experiments should *get* unphysical values ($\alpha < -1.0$), and for averaging with other measurements such values (or errors that extend below −1.0) should *not* be chopped.

α FOR $\Lambda_c^+ \to \Sigma^+\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.45±0.31±0.06	89	BISHAI	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

α FOR $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$

The experiments don't cover the complete (or same incomplete) $M(\Lambda\ell^+)$ range, but we average them together anyway.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.82^{+0.11}_{-0.07}$ OUR AVERAGE					
$-0.82^{+0.09}_{-0.06}{}^{+0.06}_{-0.03}$	700	[17] CRAWFORD	95	CLE2	$e^+e^- \approx \Upsilon(4S)$
−0.91±0.42±0.25		[18] ALBRECHT	94B	ARG	$e^+e^- \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.89^{+0.17}_{-0.11}{}^{+0.09}_{-0.05}$	350	[19] BERGFELD	94	CLE2	See CRAWFORD 95

[17] CRAWFORD 95 measures the form-factor ratio $R \equiv f_2/f_1$ for $\Lambda_c^+ \to \Lambda e^+\nu_e$ events to be $-0.25 \pm 0.14 \pm 0.08$ and from this calculates α, averaged over q^2, to be the above.

[18] ALBRECHT 94B uses Λe^+ and $\Lambda\mu^+$ events in the mass range $1.85 < M(\Lambda\ell^+) < 2.20$ GeV.

[19] BERGFELD 94 uses Λe^+ events.

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1992 edition (Physical Review **D45**, 1 June, Part II) or in earlier editions.

PDG	98	EPJ C3 1	C. Caso+	
ALBRECHT	96E	PRPL 276 223	+Andam, Binder, Bockmann+	(ARGUS Collab.)
ALEEV	96	JINRRC 3 31	+Balandin+	(Serpukhov EXCHARM Collab.)
ALEXANDER	96C	PR D53 R1013	+Bebek, Berger+	(CLEO Collab.)
ALBRECHT	95B	PL B342 397	+Hamacher, Hofmann+	(ARGUS Collab.)
AMMAR	95	PRL 74 3534	+Baringer, Bean, Besson+	(CLEO Collab.)
BISHAI	95	PL B350 256	+Fast, Gerndt, Hinson+	(CLEO Collab.)
CRAWFORD	95	PRL 75 624	+Daubenmier, Fulton+	(CLEO Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	94B	PL B326 320	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALEEV	94	PAN 57 1370 Translated from YF 57 1443.	+Balandin+	(Serpukhov BIS-2 Collab.)
AVERY	94	PL B325 257	+Freyberger, Rodriguez+	(CLEO Collab.)
BERGFELD	94	PL B323 219	+Eisenstein, Gollin, Ong+	(CLEO Collab.)
FRABETTI	94E	PL B328 193	+Cheung, Cumalat+	(FNAL E687 Collab.)
AVERY	93	PRL 71 2391	+Freyberger, Rodriguez+	(CLEO Collab.)
BOZEK	93	PL B312 247	+Barlag, Becker, Boehringer+	(CERN NA32 Collab.)
FRABETTI	93D	PRL 70 1755	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	93H	PL B314 477	+Cheung, Cumalat+	(FNAL E687 Collab.)
KUBOTA	93	PRL 71 3255	+Lattery, Nelson, Patton+	(CLEO Collab.)
ALBRECHT	92	PL B274 239	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALBRECHT	92O	ZPHY C56 1	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
BARLAG	92	PL B283 465	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
CRAWFORD	92	PR D45 752	+Fulton, Jensen, Johnson+	(CLEO Collab.)
JEZABEK	92	PL B286 175	+Rybicki, Rylko	(CRAC)
ALBRECHT	91G	PL B269 234	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
AVERY	91	PR D43 3599	+Besson, Garren, Yelton+	(CLEO Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	90B	PL B246 256	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90	PR D41 801	+Appel, Bean+	(FNAL E691 Collab.)
AVERY	90B	PRL 65 2842	+Besson, Garren, Yelton, Kinoshita+	(CLEO Collab.)
BARLAG	90D	ZPHY C48 29	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
FRABETTI	90	PL B251 639	+Bogart, Cheung, Coteus+	(FNAL E687 Collab.)
BARLAG	89	PL B218 374	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
AGUILAR-...	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87	PL B189 254	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87B	PL B199 462	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	88	SJNP 48 833 Translated from YAF 48 1310.	Begalli, Otter, Schulte, Gensch+	(LEBC-EHS Collab.)
ALBRECHT	88C	PL B207 109	+	(ARGUS Collab.)
ANJOS	88B	PRL 60 1379	+Appel+	(FNAL E691 Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
Also	87	SJNP 46 447 Translated from YAF 46 799.	Viaggi, Gessaroli+	(Photon Emulsion Collab.)
AMENDOLIA	87	ZPHY C36 513	+Bagliesi, Batignani, Beck+	(CERN NA1 Collab.)
JONES	87	ZPHY C36 593	+Jones, Kennedy, O'Neale+	(CERN WA21 Collab.)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
BOWCOCK	85	PRL 55 923	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
ALEEV	84	ZPHY C23 333	+Arefiev, Balandin, Berdyshev+	(BIS-2 Collab.)
BOSETTI	82	PL 109B 234	+Graessler+	(AACH3, BONN, CERN, MPIM, OXF)
VELLA	82	PRL 48 1515	+Trilling, Abrams, Alam+	(SLAC, LBL, UCB)
BASILE	81B	NC 62A 14	+Romeo+	(CERN, BGNA, PGIA, FRAS)
CALICCHIO	80	PL 93B 521	+	(BARI, BIRM, BRUX, CERN, EPOL, RHEL+)

$\Lambda_c(2593)^+$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

Seen in $\Lambda_c^+ \pi^+ \pi^-$ but not in $\Lambda_c^+ \pi^0$, so this is indeed an excited Λ_c^+ rather than a Σ_c^+. The $\Lambda_c^+ \pi^+ \pi^-$ mode is largely, and perhaps entirely, $\Sigma_c \pi$, which is just at threshold; thus (assuming, as has not yet been proven, that the Σ_c has $J^P = 1/2^+$) the J^P here is almost certainly $1/2^-$. This result is in accord with the theoretical expectation that this is the charm counterpart of the strange $\Lambda(1405)$.

$\Lambda_c(2593)^+$ MASS

The mass is obtained from the $m_{\Lambda_c(2593)^+} - m_{\Lambda_c^+}$ mass-difference measurements below.

VALUE (MeV)	*DOCUMENT ID*
2593.9±0.8 OUR FIT	

$m_{\Lambda_c(2593)^+} - m_{\Lambda_c^+}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
308.9±0.6 OUR FIT Error includes scale factor of 1.1.				
308.9±0.6 OUR AVERAGE Error includes scale factor of 1.1.				
309.7±0.9±0.4	19	ALBRECHT 97	ARG	$e^+e^- \approx$ 10 GeV
309.2±0.7±0.3	14	[1] FRABETTI 96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
307.5±0.4±1.0	112	[2] EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

[1] FRABETTI 96 claims a signal of 13.9 ± 4.5 events.

[2] EDWARDS 95 claims a signal of 112.5 ± 16.5 events in $\Lambda_c^+ \pi^+ \pi^-$.

$\Lambda_c(2593)^+$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$3.6^{+2.0}_{-1.3}$ OUR AVERAGE				
$2.9^{+2.9+1.8}_{-2.1-1.4}$	19	ALBRECHT 97	ARG	$e^+e^- \approx$ 10 GeV
$3.9^{+1.4+2.0}_{-1.2-1.0}$	112	EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Lambda_c(2593)^+$ DECAY MODES

$\Lambda_c^+ \pi\pi$ and its submode $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the $\Lambda_c^+ \pi^+ \pi^-$ mode seems to be largely via $\Sigma_c^{++} \pi^-$ or $\Sigma_c^0 \pi^+$.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+ \pi^+ \pi^-$	[a] ≈ 67 %
Γ_2	$\Sigma_c(2455)^{++} \pi^-$	24 ± 7 %
Γ_3	$\Sigma_c(2455)^0 \pi^+$	24 ± 7 %
Γ_4	$\Lambda_c^+ \pi^+ \pi^-$ 3-body	18 ± 10 %
Γ_5	$\Lambda_c^+ \pi^0$	not seen
Γ_6	$\Lambda_c^+ \gamma$	not seen

[a] Assuming isospin conservation, so that the other third is $\Lambda_c^+ \pi^0 \pi^0$.

$\Lambda_c(2593)^+$ BRANCHING RATIOS

$\Gamma(\Sigma_c(2455)^{++}\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ Γ_2/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.36±0.10 OUR AVERAGE			
0.37±0.12±0.13	ALBRECHT 97	ARG	$e^+e^- \approx$ 10 GeV
0.36±0.09±0.09	EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\Sigma_c(2455)^0\pi^+)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ Γ_3/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.37±0.10 OUR AVERAGE			
0.29±0.10±0.11	ALBRECHT 97	ARG	$e^+e^- \approx$ 10 GeV
0.42±0.09±0.09	EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

$[\Gamma(\Sigma_c(2455)^{++}\pi^-) + \Gamma(\Sigma_c(2455)^0\pi^+)]/\Gamma(\Lambda_c^+\pi^+\pi^-)$ $(\Gamma_2+\Gamma_3)/\Gamma_1$

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.66^{+0.13}_{-0.16}$±0.07		ALBRECHT 97	ARG	$e^+e^- \approx$ 10 GeV
>0.51	90	[3] FRABETTI 96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV

[3] The results of FRABETTI 96 are consistent with this ratio being 100%.

$\Gamma(\Lambda_c^+\pi^0)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ Γ_5/Γ_1

$\Lambda_c^+ \pi^0$ decay is forbidden by isospin conservation if this state is in fact a Λ_c.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3.53	90	EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\Lambda_c^+\gamma)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ Γ_6/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.98	90	EDWARDS 95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Lambda_c(2593)^+$ REFERENCES

ALBRECHT	97	PL B402 207	+Hamacher, Hofmann+	(ARGUS Collab.)
FRABETTI	96	PL B365 461	+Cheung, Cumalat+	(FNAL E687 Collab.)
EDWARDS	95	PRL 74 3331	+Ogg, Bellerive, Britton+	(CLEO Collab.)

$\Lambda_c(2625)^+$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

Seen in $\Lambda_c^+ \pi^+ \pi^-$ but not in $\Lambda_c^+ \pi^0$ so this is indeed an excited Λ_c^+ rather than a Σ_c^+. The spin-parity is expected to be $3/2^-$: this is presumably the charm counterpart of the strange $\Lambda(1520)$.

$\Lambda_c(2625)^+$ MASS

The mass is obtained from the $m_{\Lambda_c(2625)^+} - m_{\Lambda_c^+}$ mass-difference measurement below.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2626.6±0.8 OUR FIT Error includes scale factor of 1.2.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2626.6±0.5±1.5	42	[1] ALBRECHT 93F	ARG	See ALBRECHT 97

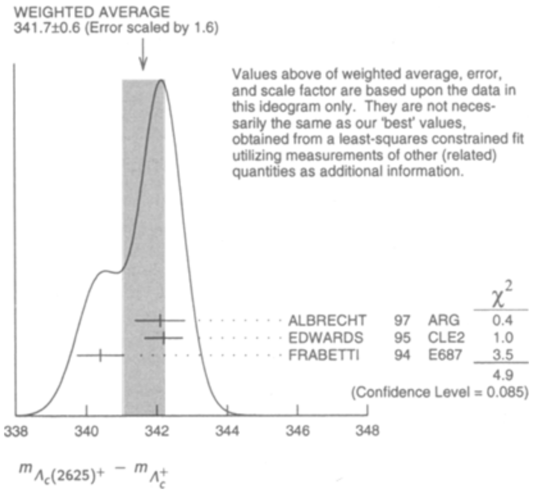
[1] ALBRECHT 93F claims a signal of 42.4 ± 8.8 events.

$m_{\Lambda_c(2625)^+} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
341.7±0.6 OUR FIT Error includes scale factor of 1.6.					
341.7±0.6 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
342.1±0.5±0.5	51	ALBRECHT	97	ARG	$e^+e^- \approx$ 10 GeV
342.2±0.2±0.5	245	[2] EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV
340.4±0.6±0.3	40	[3] FRABETTI	94	E687	γBe, $\overline{E}_\gamma$ = 220 GeV

[2] EDWARDS 95 claims a signal of 244.6 ± 19.0 events in $\Lambda_c^+\pi^+\pi^-$.

[3] FRABETTI 94 claims a signal of 39.7 ± 8.7 events.



$\Lambda_c(2625)^+$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.9	90	245	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.2	90		ALBRECHT	93F	ARG	$e^+e^- \approx \Upsilon(4S)$

$\Lambda_c(2625)^+$ DECAY MODES

$\Lambda_c^+\pi\pi$ and its submode $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi^+\pi^-$	seen
Γ_2	$\Sigma_c(2455)^{++}\pi^-$	small
Γ_3	$\Sigma_c(2455)^0\pi^+$	small
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body	large
Γ_5	$\Lambda_c^+\pi^0$	not seen
Γ_6	$\Lambda_c^+\gamma$	not seen

$\Lambda_c(2625)^+$ BRANCHING RATIOS

$\Gamma(\Sigma_c(2455)^{++}\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_2/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\Sigma_c(2455)^0\pi^+)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_3/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.07	90	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV

$[\Gamma(\Sigma_c(2455)^{++}\pi^-) + \Gamma(\Sigma_c(2455)^0\pi^+)]/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **$(\Gamma_2+\Gamma_3)/\Gamma_1$**

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.36	90		FRABETTI	94	E687	γBe, $\overline{E}_\gamma$ = 220 GeV
0.46±0.14		21	ALBRECHT	93F	ARG	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda_c^+\pi^+\pi^-$ 3-body$)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_4/Γ_1**

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.54±0.14	16	ALBRECHT	93F	ARG	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda_c^+\pi^0)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_5/Γ_1**

$\Lambda_c^+\pi^0$ decay is forbidden by isospin conservation if this state is in fact a Λ_c.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.91	90	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\Lambda_c^+\gamma)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_6/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.52	90	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV

$\Lambda_c(2625)^+$ REFERENCES

ALBRECHT	97	PL B402 207	+Hamacher, Hofmann+	(ARGUS Collab.)
EDWARDS	95	PRL 74 3331	+Ogg, Bellerive, Britton+	(CLEO Collab.)
FRABETTI	94	PRL 72 961	+Cheung, Cumalat+	(FNAL E687 Collab.)
ALBRECHT	93F	PL B317 227	+Ehrlichmann, Hamacher+	(ARGUS Collab.)

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

J^P is not confirmed. $1/2^+$ is the quark model prediction.

$\Sigma_c(2455)$ MASSES

The masses are obtained from the mass-difference measurements that follow.

$\Sigma_c(2455)^{++}$ MASS

VALUE (MeV)	DOCUMENT ID
2452.8±0.6 OUR FIT	

$\Sigma_c(2455)^+$ MASS

VALUE (MeV)	DOCUMENT ID
2453.6±0.9 OUR FIT	

$\Sigma_c(2455)^0$ MASS

VALUE (MeV)	DOCUMENT ID
2452.2±0.6 OUR FIT	

$m_{\Sigma_c(2455)} - m_{\Lambda_c^+}$

$m_{\Sigma_c^{++}} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
167.87± 0.19 OUR FIT					
167.87± 0.20 OUR AVERAGE					
167.76± 0.29±0.15	122	AITALA	96B	E791	$\pi^- N$, 500 GeV
167.6 ± 0.6 ±0.6	56	FRABETTI	96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
168.2 ± 0.3 ±0.2	126	CRAWFORD	93	CLE2	$e^+e^- \approx \Upsilon(4S)$
167.8 ± 0.4 ±0.3	54	BOWCOCK	89	CLEO	e^+e^- 10 GeV
168.2 ± 0.5 ±1.6	92	ALBRECHT	88D	ARG	e^+e^- 10 GeV
167.4 ± 0.5 ±2.0	46	DIESBURG	87	SPEC	nA ∼ 600 GeV
167 ± 1	2	JONES	87	HBC	νp in BEBC
168 ± 3	6	BALTAY	79	HLBC	ν Ne-H in 15-ft
• • • We do not use the following data for averages, fits, limits, etc. • • •					
166 ± 1	1	BOSETTI	82	HBC	See JONES 87
166 ±15	1	CAZZOLI	75	HBC	νp in BNL 7-ft

$m_{\Sigma_c^+} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
168.7±0.6 OUR FIT					
168 ±3	1	CALICCHIO	80	HBC	νp in BEBC-TST
• • • We do not use the following data for averages, fits, limits, etc. • • •					
168.5±0.4±0.2	111	[1] CRAWFORD	93	CLE2	$e^+e^- \approx \Upsilon(4S)$

[1] This result enters the fit through $m_{\Sigma_c^+} - m_{\Sigma_c^0}$ below.

$m_{\Sigma_c^0} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
167.30±0.20 OUR FIT					
167.31±0.21 OUR AVERAGE					
167.38±0.29±0.15	143	AITALA	96B	E791	$\pi^- N$, 500 GeV
167.8 ±0.6 ±0.2		ALEEV	96	SPEC	n nucleus, 50 GeV/c
166.6 ±0.5 ±0.6	69	FRABETTI	96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
167.1 ±0.3 ±0.2	124	CRAWFORD	93	CLE2	$e^+e^- \approx \Upsilon(4S)$
168.4 ±1.0 ±0.3	14	ANJOS	89D	E691	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
167.9 ±0.5 ±0.3	48	[2] BOWCOCK	89	CLEO	e^+e^- 10 GeV
167.0 ±0.5 ±1.6	70	[2] ALBRECHT	88D	ARG	e^+e^- 10 GeV
178.2 ±0.4 ±2.0	85	[3] DIESBURG	87	SPEC	nA ∼ 600 GeV
163 ±2	1	AMMAR	86	EMUL	νA

[2] This result enters the fit through $m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$ given below.

[3] See the note on DIESBURG 87 in the $m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$ section below.

$\Sigma_c(2455)$ MASS DIFFERENCES

$m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.57±0.23 OUR FIT			
0.66±0.28 OUR AVERAGE	Error includes scale factor of 1.1.		
+ 0.38±0.40±0.15	AITALA 96B	E791	$\pi^- N$, 500 GeV
1.1 ±0.4 ±0.1	CRAWFORD 93	CLE2	$e^+e^- \approx \Upsilon(4S)$
− 0.1 ±0.6 ±0.1	BOWCOCK 89	CLEO	e^+e^- 10 GeV
+ 1.2 ±0.7 ±0.3	ALBRECHT 88D	ARG	$e^+e^- \sim$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−10.8 ±2.9	[4] DIESBURG 87	SPEC	$nA \sim 600$ GeV

[4] DIESBURG 87 is completely incompatible with the other experiments, which is surprising since it agrees with them about $m_{\Sigma_c(2455)^{++}} - m_{\Lambda_c^+}$. We go with the majority here.

$m_{\Sigma_c^+} - m_{\Sigma_c^0}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1.4±0.6 OUR FIT			
1.4±0.5±0.3	CRAWFORD 93	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Sigma_c(2455)$ DECAY MODES

$\Lambda_c^+\pi$ is the only strong decay allowed to a Σ_c having this mass.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi$	≈ 100 %

$\Sigma_c(2455)$ REFERENCES

AITALA	96B	PL B379 292	+Amato, Anjos+	(FNAL E791 Collab.)
ALEEV	96	JINRRC 3 31	+Balandin+	(Serpukhov EXCHARM Collab.)
FRABETTI	96	PL B365 461	+Cheung, Cumalat+	(FNAL E687 Collab.)
CRAWFORD	93	PRL 71 3259	+Daubenmier, Fulton+	(CLEO Collab.)
ANJOS	89D	PRL 62 1721	+Appel, Bean, Bracker, Browder+	(FNAL E691 Collab.)
BOWCOCK	89	PRL 62 1240	+Kinoshita, Pipkin, Procario, Wilson+	(CLEO Collab.)
ALBRECHT	88D	PL B211 489	+Boeckmann, Glaeser+	(ARGUS Collab.)
DIESBURG	87	PRL 59 2711	+Ladbury, Binkley+	(FNAL E400 Collab.)
JONES	87	ZPHY C36 593	+Jones, Kennedy, O'Neale+	(CERN WA21 Collab.)
AMMAR	86	JETPL 43 515 Translated from ZETFP 43 401.	+Ammosov, Bakic, Baranov, Burnett+	(ITEP)
BOSETTI	82	PL 109B 234	+Graessler+	(AACH3, BONN, CERN, MPIM, OXF)
CALICCHIO	80	PL 93B 521	+	(BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
BALTAY	79	PRL 42 1721	+Caroumbalis, French, Hibbs+	(COLU, BNL)
CAZZOLI	75	PRL 34 1125	+Cnops, Connolly, Louttit, Murtagh+	(BNL)

$\Sigma_c(2520)$

$I(J^P) = 1(?^?)$ Status: ∗∗∗

Seen in the $\Lambda_c^+\pi^\pm$ mass spectrum. The natural assignment is that this is the $J^P = 3/2^+$ excitation of the $\Sigma_c(2455)$, the charm counterpart of the $\Sigma(1385)$.

$\Sigma_c(2520)$ MASSES

The masses are obtained from the mass-difference measurements that follow.

$\Sigma_c(2520)^{++}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2519.4±1.5 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2530 ±5 ±5	6	[1] AMMOSOV 93	HLBC	$\nu p \rightarrow \mu^- \Sigma_c(2530)^{++}$

[1] AMMOSOV 93 sees a cluster of 6 events and estimates the background to be 1 event.

$\Sigma_c(2520)^0$ MASS

VALUE (MeV)	DOCUMENT ID
2517.5±1.4 OUR FIT	

$\Sigma_c(2520)$ MASS DIFFERENCES

$m_{\Sigma_c(2520)^{++}} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
234.5±1.4 OUR FIT				
234.5±1.1±0.8	677	BRANDENB... 97	CLE2	$e^+e^- \approx \Upsilon(4S)$

$m_{\Sigma_c(2520)^0} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
232.6±1.3 OUR FIT				
232.6±1.0±0.8	504	BRANDENB... 97	CLE2	$e^+e^- \approx \Upsilon(4S)$

$m_{\Sigma_c(2520)^{++}} - m_{\Sigma_c(2520)^0}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1.9±1.9 OUR FIT			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.9±1.4±1.0	[2] BRANDENB... 97	CLE2	$e^+e^- \approx \Upsilon(4S)$

[2] This BRANDENBURG 97 result is redundant with measurements in earlier entries.

$\Sigma_c(2520)$ WIDTHS

$\Sigma_c(2520)^{++}$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$17.9^{+3.8}_{-3.2}\pm4.0$	677	BRANDENB... 97	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Sigma_c(2520)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$13.0^{+3.7}_{-3.0}\pm4.0$	504	BRANDENB... 97	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Sigma_c(2520)$ REFERENCES

BRANDENB...	97	PRL 78 2304	Brandenburg, Briere, Kim, Liu+	(CLEO Collab.)
AMMOSOV	93	JETPL 58 247 Translated from ZETFP 58 241.	+Vasil'ev, Ivanilov, Ivanov+	(SERP)

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

According to the quark model, the Ξ_c^+ (quark content usc) and Ξ_c^0 form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P has actually been measured.

Ξ_c^+ MASS

The fit uses the Ξ_c^+ and Ξ_c^0 mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2465.6± 1.4 OUR FIT				
2465.9± 1.4 OUR AVERAGE				
2467.0± 1.6± 2.0	147	EDWARDS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$
2464.4± 2.0± 1.4	30	FRABETTI 93B	E687	γBe, $\overline{E}_\gamma$= 220 GeV
2465.1± 3.6± 1.9	30	ALBRECHT 90F	ARG	e^+e^- at $\Upsilon(4S)$
2467 ± 3 ± 4	23	ALAM 89	CLEO	e^+e^- 10.6 GeV
2466.5± 2.7± 1.2	5	BARLAG 89C	ACCM	π^- Cu 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2459 ± 5 ±30	56	[1] COTEUS 87	SPEC	$nA \simeq$ 600 GeV
2460 ±25	82	BIAGI 83	SPEC	Σ^- Be 135 GeV

[1] Although COTEUS 87 claims to agree well with BIAGI 83 on the mass and width, there appears to be a discrepancy between the two experiments. BIAGI 83 sees a single peak (stated significance about 6 standard deviations) in the $\Lambda K^-\pi^+\pi^+$ mass spectrum. COTEUS 87 sees *two* peaks in the same spectrum, one at the Ξ_c^+ mass, the other 75 MeV lower. The latter is attributed to $\Xi_c^+ \rightarrow \Sigma^0 K^-\pi^+\pi^+ \rightarrow (\Lambda\gamma)K^-\pi^+\pi^+$, with the γ unseen. The *combined* significance of the double peak is stated to be 5.5 standard deviations. But the absence of any trace of a lower peak in BIAGI 83 seems to us to throw into question the interpretation of the lower peak of COTEUS 87.

Ξ_c^+ MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
$0.35^{+0.07}_{-0.04}$ OUR AVERAGE				
$0.41^{+0.11}_{-0.08}\pm0.02$	30	FRABETTI 93B	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$0.20^{+0.11}_{-0.06}$	6	BARLAG 89C	ACCM	π^- (K^-) Cu 230 GeV
$0.40^{+0.18}_{-0.12}\pm0.10$	102	COTEUS 87	SPEC	$nA \simeq$ 600 GeV
$0.48^{+0.21}_{-0.15}{}^{+0.20}_{-0.10}$	53	BIAGI 85C	SPEC	Σ^- Be 135 GeV

Ξ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K^-\pi^+\pi^+$	seen
Γ_2	$\Lambda\overline{K}^*(892)^0\pi^+$	not seen
Γ_3	$\Sigma(1385)^+K^-\pi^+$	not seen
Γ_4	$\Sigma^+K^-\pi^+$	seen
Γ_5	$\Sigma^+\overline{K}^*(892)^0$	seen
Γ_6	$\Sigma^0K^-\pi^+\pi^+$	seen
Γ_7	$\Xi^0\pi^+$	seen
Γ_8	$\Xi^-\pi^+\pi^+$	seen
Γ_9	$\Xi(1530)^0\pi^+$	not seen
Γ_{10}	$\Xi^0\pi^+\pi^0$	seen
Γ_{11}	$\Xi^0\pi^+\pi^+\pi^-$	seen
Γ_{12}	$\Xi^0 e^+\nu_e$	seen

Ξ_c^+ BRANCHING RATIOS

$\Gamma(\Lambda K^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	56	COTEUS 87	SPEC	$nA \simeq$ 600 GeV
seen	82	[2] BIAGI 83	SPEC	Σ^- Be 135 GeV

[2] BIAGI 85B looks for but does not see the Ξ_c^+ in $pK^-\overline{K}^0\pi^+$ ($\Gamma(pK^-\overline{K}^0\pi^+)$ / $\Gamma(\Lambda K^-\pi^+\pi^+)$ <0.08 with 90% CL), $p2K^-2\pi^+$ ($\Gamma(p2K^-2\pi^+)$ / $\Gamma(\Lambda K^-\pi^+\pi^+)$ <0.03, 90% CL), $\Omega^-K^+\pi^+$, $\Lambda K^{*0}\pi^+$, and $\Sigma(1385)^+K^-\pi^+$.

$\Gamma(\Lambda K^-\pi^+\pi^+)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_1/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.58±0.16±0.07	61	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda\overline{K}^*(892)^0\pi^+)/\Gamma(\Lambda K^-\pi^+\pi^+)$ Γ_2/Γ_1

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.5	90	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma(1385)^+K^-\pi^+)/\Gamma(\Lambda K^-\pi^+\pi^+)$ Γ_3/Γ_1

Unseen decay modes of the $\Sigma(1385)^+$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.7	90	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+K^-\pi^+)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_4/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.18±0.26±0.17	119	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.09^{+0.13}_{-0.06}{}^{+0.03}_{-0.02}$	5	BARLAG 89C	ACCM	$2\ \Sigma^+K^-\pi^+$, $3\ \Xi^-\pi^+\pi^+$

$\Gamma(\Sigma^+\overline{K}^*(892)^0)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_5/Γ_8

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.92±0.27±0.14	61	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	59	AVERY 95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^0K^-\pi^+\pi^+)/\Gamma(\Lambda K^-\pi^+\pi^+)$ Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.84±0.36	47	[3] COTEUS 87	SPEC	$nA \simeq$ 600 GeV

[3] See, however, the note on the COTEUS 87 Ξ_c^+ mass measurement.

$\Gamma(\Xi^0\pi^+)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_7/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.55±0.13±0.09	39	EDWARDS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	131	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$
seen	160	AVERY 95	CLE2	$e^+e^- \approx \Upsilon(4S)$
seen	30	FRABETTI 93B	E687	γBe, $\overline{E}_\gamma$= 220 GeV
seen	30	ALBRECHT 90F	ARG	e^+e^- at $\Upsilon(4S)$
seen	23	ALAM 89	CLEO	e^+e^- 10.6 GeV

$\Gamma(\Xi(1530)^0\pi^+)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_9/Γ_8

Unseen decay modes of the $\Xi(1530)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.2	90	BERGFELD 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0\pi^+\pi^0)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_{10}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.34±0.57±0.37	81	EDWARDS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi(1530)^0\pi^+)/\Gamma(\Xi^0\pi^+\pi^0)$ Γ_9/Γ_{10}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.3	90	EDWARDS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0\pi^+\pi^+\pi^-)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_{11}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.74±0.42±0.27	57	EDWARDS 96	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0e^+\nu_e)/\Gamma(\Xi^-\pi^+\pi^+)$ Γ_{12}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$2.3\pm0.6^{+0.3}_{-0.6}$	41	ALEXANDER 95B	CLE2	$e^+e^- \approx \Upsilon(4S)$

Ξ_c^+ REFERENCES

BERGFELD	96	PL B365 431	+Eisenstein, Ernst+	(CLEO Collab.)
EDWARDS	96	PL B373 261	+McLean, Ogg+	(CLEO Collab.)
ALEXANDER	95B	PRL 74 3113	+Bebek, Berkelman+	(CLEO Collab.)
Also	95E	PRL 75 4155 (erratum)		
AVERY	95	PRL 75 4364	+Freyberger, Lingel+	(CLEO Collab.)
FRABETTI	93B	PRL 70 1381	+Cheung, Cumalat+	(FNAL E687 Collab.)
ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+	(ARGUS Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
BARLAG	89C	PL B233 522	+Boehringer, Bosman+	(ACCMOR Collab.)
COTEUS	87	PRL 59 1530	+Binkley+	(FNAL E400 Collab.)
BIAGI	85B	ZPHY C28 175	+Bourquin, Britten+	(CERN WA62 Collab.)
BIAGI	85C	PL 150B 230	+Bourquin, Britten+	(CERN WA62 Collab.)
BIAGI	83	PL 122B 455	+Bourquin, Britten+	(CERN WA62 Collab.)

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

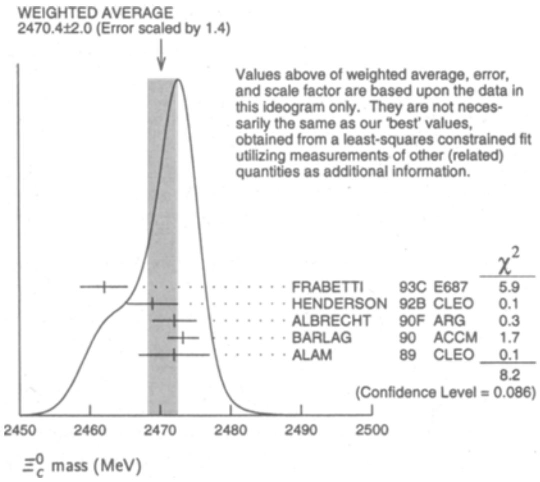
According to the quark model, the Ξ_c^0 (quark content dsc) and Ξ_c^+ form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P has actually been measured.

Ξ_c^0 MASS

The fit uses the Ξ_c^0 and Ξ_c^+ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2470.3±1.8 OUR FIT Error includes scale factor of 1.3.				
2470.4±2.0 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
2462.1±3.1±1.4	42	[1] FRABETTI 93C	E687	γBe, $\overline{E}_\gamma$= 220 GeV
2469 ±2 ±3	9	HENDERSON 92B	CLEO	Ω^-K^+
2472.1±2.7±1.6	54	ALBRECHT 90F	ARG	e^+e^- at $\Upsilon(4S)$
2473.3±1.9±1.2	4	BARLAG 90	ACCM	π^- (K^-) Cu 230 GeV
2472 ±3 ±4	19	ALAM 89	CLEO	e^+e^- 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2471 ±3 ±4	14	AVERY 89	CLEO	See ALAM 89

[1] The FRABETTI 93C mass is well below the other measurements.



$m_{\Xi_c^0} - m_{\Xi_c^+}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4.7±2.1 OUR FIT Error includes scale factor of 1.2.			
6.3±2.3 OUR AVERAGE			
+7.0±4.5±2.2	ALBRECHT 90F	ARG	e^+e^- at $\Upsilon(4S)$
+6.8±3.3±0.5	BARLAG 90	ACCM	π^- (K^-) Cu 230 GeV
+5 ±4 ±1	ALAM 89	CLEO	$\Xi_c^0 \to \Xi^-\pi^+$, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

Ξ_c^0 MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
$0.098^{+0.023}_{-0.015}$ OUR AVERAGE				
$0.101^{+0.025}_{-0.017}\pm0.005$	42	FRABETTI 93C	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$0.082^{+0.059}_{-0.030}$	4	BARLAG 90	ACCM	π^- (K^-) Cu 230 GeV

Ξ_c^0 DECAY MODES

	Mode	Fraction (Γ_j/Γ)
Γ_1	$\Lambda \overline{K}^0$	seen
Γ_2	$\Xi^- \pi^+$	seen
Γ_3	$\Xi^- \pi^+ \pi^+ \pi^-$	seen
Γ_4	$p K^- \overline{K}^*(892)^0$	seen
Γ_5	$\Omega^- K^+$	seen
Γ_6	$\Xi^- e^+ \nu_e$	seen
Γ_7	$\Xi^- \ell^+$ anything	seen

Ξ_c^0 BRANCHING RATIOS

$\Gamma(\Lambda \overline{K}^0)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	7	ALBRECHT	95B	ARG	$e^+ e^- \approx 10.4$ GeV

$\Gamma(\Xi^- \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+ \pi^-)$ — Γ_2/Γ_3

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.30±0.12±0.05	ALBRECHT	90F	ARG	$e^+ e^-$ at $\Upsilon(4S)$

$\Gamma(p K^- \overline{K}^*(892)^0)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV

$\Gamma(\Omega^- K^+)/\Gamma(\Xi^- \pi^+)$ — Γ_5/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.50±0.21±0.05	9	HENDERSON	92B	CLEO	$e^+ e^- \approx 10.6$ GeV

$\Gamma(\Xi^- e^+ \nu_e)/\Gamma(\Xi^- \pi^+)$ — Γ_6/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$3.1 \pm 1.0^{+0.3}_{-0.5}$	54	ALEXANDER	95B	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^- \ell^+ \text{anything})/\Gamma(\Xi^- \pi^+)$ — Γ_7/Γ_2

The ratio is for the *average* (not the sum) of the $\Xi^- e^+$ anything and $\Xi^- \mu^+$ anything modes.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.96±0.43±0.18	18	ALBRECHT	93B	ARG	$e^+ e^- \approx 10.4$ GeV

$\Gamma(\Xi^- \ell^+ \text{anything})/\Gamma(\Xi^- \pi^+ \pi^+ \pi^-)$ — Γ_7/Γ_3

The ratio is for the *average* (not the sum) of the $\Xi^- e^+$ anything and $\Xi^- \mu^+$ anything modes.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.29±0.12±0.04	18	ALBRECHT	93B	ARG	$e^+ e^- \approx 10.4$ GeV

Ξ_c^0 REFERENCES

ALBRECHT	95B	PL B342 397	+Hamacher, Hofmann+	(ARGUS Collab.)
ALEXANDER	95B	PRL 74 3113	+Bebek, Berkelman+	(CLEO Collab.)
Also	95E	PRL 75 4155 (erratum)		
ALBRECHT	93B	PL B303 368	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
FRABETTI	93C	PRL 70 2058	+Cheung, Cumalat+	(FNAL E687 Collab.)
HENDERSON	92B	PL B283 161	+Kinoshita, Pipkin, Saulnier+	(CLEO Collab.)
ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+	(ARGUS Collab.)
BARLAG	90	PL B236 495	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
AVERY	89	PRL 62 863	+Besson, Garren, Yelton, Bowcock+	(CLEO Collab.)

$\Xi_c(2645)$

$I(J^P) = ?(?^?)$ Status: ∗∗∗

A narrow peak seen in the $\Xi_c \pi$ mass spectrum. The natural assignment is that this is the $J^P = 3/2^+$ excitation of the Ξ_c in the same SU(4) multiplet as the $\Delta(1232)$.

$\Xi_c(2645)$ MASSES

The masses are obtained from the mass-difference measurements that follow.

$\Xi_c(2645)^+$ MASS

VALUE (MeV)	*DOCUMENT ID*
2644.6±2.1 OUR FIT	Error includes scale factor of 1.2.

$\Xi_c(2645)^0$ MASS

VALUE (MeV)	*DOCUMENT ID*
2643.8±1.8 OUR FIT	

$m_{\Xi_c(2645)} - m_{\Xi_c}$

$m_{\Xi_c(2645)^+} - m_{\Xi_c^0}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
174.3±1.1 OUR FIT					
174.3±0.5±1.0	34	GIBBONS	96	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$m_{\Xi_c(2645)^0} - m_{\Xi_c^+}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
178.2±1.1 OUR FIT					
178.2±0.5±1.0	55	AVERY	95	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Xi_c(2645)$ WIDTHS

$\Xi_c(2645)^+$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<3.1	90	GIBBONS	96	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Xi_c(2645)^0$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<5.5	90	55	AVERY	95	CLE2	$e^+ e^- \approx \Upsilon(4S)$

$\Xi_c(2645)$ DECAY MODES

$\Xi_c \pi$ is the only strong decay allowed to a Ξ_c resonance having this mass.

	Mode	Fraction (Γ_j/Γ)
Γ_1	$\Xi_c^0 \pi^+$	seen
Γ_2	$\Xi_c^+ \pi^-$	seen

$\Xi_c(2645)$ REFERENCES

GIBBONS	96	PRL 77 810	+Johnson, Kwon+	(CLEO Collab.)
AVERY	95	PRL 75 4364	+Freyberger, Lingel+	(CLEO Collab.)

Ω_c^0

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

The quantum numbers have not been measured, but are simply assigned in accord with the quark model, in which the Ω_c^0 is the *ssc* ground state.

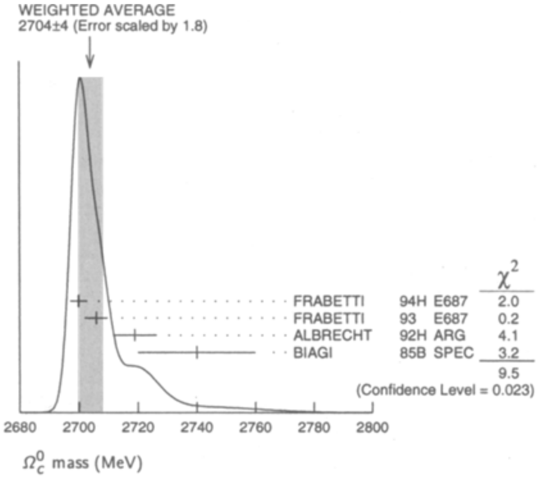
Ω_c^0 MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2704 ± 4 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			
2699.9± 1.5±2.5	42	[1] FRABETTI	94H	E687	γBe, $\overline{E}_\gamma$= 221 GeV
2705.9± 3.3±2.0	10	[2] FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV
2719.0± 7.0±2.5	11	[3] ALBRECHT	92H	ARG	$e^+e^- \approx$ 10.6 GeV
2740 ±20	3	BIAGI	85B	SPEC	Σ^- Be 135 GeV/c

[1] FRABETTI 94H claims a signal of 42.5 ± 8.8 $\Sigma^+ K^- K^- \pi^+$ events. The background is about 24 events.

[2] FRABETTI 93 claims a signal of 10.3 ± 3.9 $\Omega^- \pi^+$ events above a background of 5.8 events.

[3] ALBRECHT 92H claims a signal of 11.5 ± 4.3 $\Xi^- K^- \pi^+ \pi^+$ events. The background is about 5 events.



Ω_c^0 MEAN LIFE

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.064±0.020 OUR AVERAGE					
$0.055^{+0.013}_{-0.011}{}^{+0.018}_{-0.023}$	86	ADAMOVICH	95B	WA89	$\Omega^- \pi^- \pi^+ \pi^+$, $\Xi^- K^- \pi^+ \pi^+$
$0.086^{+0.027}_{-0.020}\pm0.028$	25	FRABETTI	95D	E687	$\Sigma^+ K^- K^- \pi^+$

Ω_c^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma^+ K^- K^- \pi^+$	seen
Γ_2	$\Xi^- K^- \pi^+ \pi^+$	seen
Γ_3	$\Omega^- \pi^+$	seen
Γ_4	$\Omega^- \pi^- \pi^+ \pi^+$	seen

Ω_c^0 BRANCHING RATIOS

$\Gamma(\Sigma^+ K^- K^- \pi^+)/\Gamma_{\rm total}$ **Γ_1/Γ**

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	42	FRABETTI	94H	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Xi^- K^- \pi^+ \pi^+)/\Gamma_{\rm total}$ **Γ_2/Γ**

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	11	ALBRECHT	92H	ARG	$e^+e^- \approx$ 10.6 GeV
seen	3	BIAGI	85B	SPEC	Σ^- Be 135 GeV/c

$\Gamma(\Omega^- \pi^+)/\Gamma_{\rm total}$ **Γ_3/Γ**

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	10	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Xi^- K^- \pi^+ \pi^+)/\Gamma(\Omega^- \pi^+)$ **Γ_2/Γ_3**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Omega^- \pi^- \pi^+ \pi^+)/\Gamma(\Omega^- \pi^+)$ **Γ_4/Γ_3**

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen		ADAMOVICH	95B	WA89	Σ^- 340 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

Ω_c^0 REFERENCES

ADAMOVICH	95B	PL B358 151	+Albertson, Alexandrov+	(CERN WA89 Collab.)
FRABETTI	95D	PL B357 678	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94H	PL B338 106	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	93	PL B300 190	+Cheung, Cumalat, Dallapiccola+	(FNAL E687 Collab.)
ALBRECHT	92H	PL B288 367	+Cronstroem, Ehrlichmann, Hamacher+	(ARGUS Collab.)
BIAGI	85B	ZPHY C28 175	+Bourquin, Britten+	(CERN WA62 Collab.)

BOTTOM BARYONS
$(B = -1)$

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

In the quark model, a Λ_b^0 is an isospin-0 udb state. The lowest Λ_b^0 ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Λ_b^0 MASS

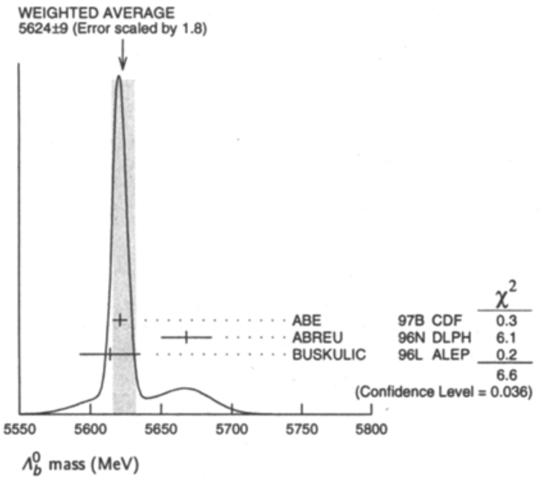
VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5624± 9 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			
5621± 4± 3		[1] ABE	97B	CDF	$p\overline{p}$ at 1.8 TeV
5668± 16± 8	4	[2] ABREU	96N	DLPH	$e^+e^- \rightarrow Z$
5614± 21± 4	4	[2] BUSKULIC	96L	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen		[3] ABE	93B	CDF	Sup. by ABE 97B
5640± 50±30	16	[4] ALBAJAR	91E	UA1	$p\overline{p}$ 630 GeV
5640^{+100}_{-210}	52	BARI	91	SFM	$\Lambda_b^0 \rightarrow pD^0\pi^-$
5650^{+150}_{-200}	90	BARI	91	SFM	$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$

[1] ABE 97B observed 38 events above a background 18 ± 1.6 events in the mass range 5.60–5.65 GeV/c^2, a significance of > 3.4 standard deviations.

[2] Uses 4 fully reconstructed Λ_b events.

[3] ABE 93B states that, based on the signal claimed by ALBAJAR 91E, CDF should have found 30 ± 23 $\Lambda_b^0 \rightarrow J/\psi(1S)\Lambda$ events. Instead, CDF found not more than 2 events.

[4] ALBAJAR 91E claims 16 ± 5 events above a background of 9 ± 1 events, a significance of about 5 standard deviations.



Λ_b^0 MEAN LIFE

These are actually measurements of the average lifetime of weakly decaying b baryons weighted by generally unknown production rates, branching fractions, and detection efficiencies. Presumably, the mix is mainly Λ_b^0, with some Ξ_b^0 and Ξ_b^-.

See b-baryon Admixture section for data on b-baryon mean life average over species of b-baryon particles.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.24±0.08 OUR EVALUATION					
$1.29^{+0.24}_{-0.22}\pm0.06$		[5] ACKERSTAFF	98G	OPAL	$e^+e^- \rightarrow Z$
1.21±0.11		[5] BARATE	98D	ALEP	$e^+e^- \rightarrow Z$
1.32±0.15±0.07		ABE	96M	CDF	Excess $\Lambda_c\ell^-$, decay lengths
$1.19^{+0.21}_{-0.18}{}^{+0.07}_{-0.08}$		ABREU	96D	DLPH	Excess $\Lambda_c\ell^-$, decay lengths
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.14^{+0.22}_{-0.19}\pm0.07$	69	AKERS	95K	OPAL	Repl. by ACKERSTAFF 98G
$1.02^{+0.23}_{-0.18}\pm0.06$	44	BUSKULIC	95L	ALEP	Repl. by BARATE 98D

[5] Measured using $\Lambda_c\ell^-$ and $\Lambda\ell^+\ell^-$.

Λ_b^0 DECAY MODES

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction B($b \rightarrow \Lambda_b$) and are evaluated for our value B($b \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1})$%.

The branching fractions B(b-baryon → $\Lambda\ell^-\overline{\nu}_\ell$anything) and B($\Lambda_b^0 \rightarrow \Lambda_c^+\ell^-\overline{\nu}_\ell$anything) are not pure measurements because the underlying measured products of these with B($b \rightarrow \Lambda_b$) were used to determine B($b \rightarrow \Lambda_b$), as described in the note "Production and Decay of b-Flavored Hadrons."

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$J/\psi(1S)\Lambda$	$(4.7\pm2.8)\times10^{-4}$	
Γ_2	$pD^0\pi^-$		
Γ_3	$\Lambda_c^+\pi^-$	seen	
Γ_4	$\Lambda_c^+a_1(1260)^-$	seen	
Γ_5	$\Lambda_c^+\pi^+\pi^-\pi^-$		
Γ_6	$\Lambda K^0 2\pi^+ 2\pi^-$		
Γ_7	$\Lambda_c^+\ell^-\overline{\nu}_\ell$anything	[a] $(9.0^{+3.1}_{-3.8})$ %	
Γ_8	$p\pi^-$	$< 5.0 \times 10^{-5}$	90%
Γ_9	pK^-	$< 5.0 \times 10^{-5}$	90%

[a] Not a pure measurement. See note at head of Λ_b^0 Decay Modes.

Λ_b^0 BRANCHING RATIOS

$\Gamma(J/\psi(1S)\Lambda)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.7± 2.1± 1.9		[6] ABE	97B	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$178.2\pm108.9^{+54.7}_{-68.8}$	16	[7] ALBAJAR	91E	UA1	$J/\psi(1S) \rightarrow \mu^+\mu^-$

[6] ABE 97B reports (0.037 ± 0.017(stat)±0.007(sys))% for B($b \rightarrow \Lambda_b$) = 0.1 and for B($B^0 \rightarrow J/\psi(1S)K_S^0$) = 0.037%. We rescale to our PDG 97 best value B($b \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1})$% and B($B^0 \rightarrow J/\psi(1S)K_S^0$) = (0.044 ± 0.006)%. Our first error is their experiments's error and our second error is the systematic error from using our best value.

[7] ALBAJAR 91E reports 180 ± 110 for B($\overline{b} \rightarrow \Lambda_b$) = 0.10. We rescale to our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(pD^0\pi^-)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	52	BARI	91	SFM	$D^0 \rightarrow K^-\pi^+$
seen		BASILE	81	SFM	$D^0 \rightarrow K^-\pi^+$

$\Gamma(\Lambda_c^+\pi^-)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	3	ABREU	96N	DLPH	$\Lambda_c^+ \rightarrow pK^-\pi^+$
seen	4	BUSKULIC	96L	ALEP	$\Lambda_c^+ \rightarrow pK^-\pi^+$, $p\overline{K}^0$, $\Lambda\pi^+\pi^+\pi^-$

$\Gamma(\Lambda_c^+a_1(1260)^-)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	1	ABREU	96N	DLPH	$\Lambda_c^+ \rightarrow pK^-\pi^+$, $a_1^- \rightarrow \rho^0\pi^- \rightarrow \pi^+\pi^-\pi^-$

$\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	90	BARI	91	SFM	$\Lambda_c^+ \rightarrow pK^-\pi^+$

$\Gamma(\Lambda K^0 2\pi^+ 2\pi^-)/\Gamma_{\rm total}$ Γ_6/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	4	[8] ARENTON	86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$

[8] See the footnote to the ARENTON 86 mass value.

$\Gamma(\Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_7/Γ

The values and averages in this section serve only to show what values result if one assumes our B($b \to \Lambda_b$). They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine B($b \to \Lambda_b$) as described in the note on "Production and Decay of b-Flavored Hadrons."

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.090^{+0.031}_{-0.038}$ OUR AVERAGE				
$0.085 \pm 0.015^{+0.026}_{-0.033}$		[9] BARATE	98D ALEP	$e^+ e^- \to Z$
$0.12\ ^{+0.04}_{-0.03}\ ^{+0.04}_{-0.05}$	29	[10] ABREU	95S DLPH	$e^+ e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.075 \pm 0.018^{+0.023}_{-0.029}$	55	[11] BUSKULIC	95L ALEP	Repl. by BARATE 98D
$0.15\ \pm 0.06\ ^{+0.05}_{-0.06}$	21	[12] BUSKULIC	92E ALEP	$\Lambda_c^+ \to p K^- \pi^+$

[9] BARATE 98D reports [B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$anything) × B($\overline{b} \to \Lambda_b$)] = 0.0086 ± 0.0007 ± 0.0014. We divide by our best value B($\overline{b} \to \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Measured using $\Lambda_c \ell^-$ and $\Lambda \ell^+ \ell^-$.

[10] ABREU 95S reports [B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$anything) × B($\overline{b} \to \Lambda_b$)] = $0.0118 \pm 0.0026^{+0.0031}_{-0.0021}$. We divide by our best value B($\overline{b} \to \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[11] BUSKULIC 95L reports [B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$anything) × B($\overline{b} \to \Lambda_b$)] = 0.00755 ± 0.0014 ± 0.0012. We divide by our best value B($\overline{b} \to \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[12] BUSKULIC 92E reports [B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$anything) × B($\overline{b} \to \Lambda_b$)] = 0.015 ± 0.0035 ± 0.0045. We divide by our best value B($\overline{b} \to \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Superseded by BUSKULIC 95L.

$\Gamma(p\pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<5.0 \times 10^{-5}$	90	[13] BUSKULIC	96V ALEP	$e^+ e^- \to Z$

[13] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

$\Gamma(pK^-)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<5.0 \times 10^{-5}$	90	[14] BUSKULIC	96V ALEP	$e^+ e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-4}$	90	[15] ADAM	96D DLPH	$e^+ e^- \to Z$

[14] BUSKULIC 96V assumes PDG 96 production fractions for B^0, B^+, B_s, b baryons.

[15] ADAM 96D assumes $f_{B^0} = f_{B^-} = 0.39$ and $f_{B_s} = 0.12$.

Λ_b^0 REFERENCES

ACKERSTAFF	98G	PL B426 161	K. Ackerstaff+	(OPAL Collab.)
BARATE	98D	EPJ C2 197	R. Barate+	(ALEPH Collab.)
ABE	97B	PR D55 1142	+Akimoto, Akopian, Albrow+	(CDF Collab.)
PDG	97	Unofficial 1997 WWW edition		
ABE	96M	PRL 77 1439	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABREU	96D	ZPHY C71 199	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	96N	PL B374 351	+Adam, Adye, Agasi+	(DELPHI Collab.)
ADAM	96D	ZPHY C72 207	W. Adam+	(DELPHI Collab.)
BUSKULIC	96L	PL B380 442	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96V	PL B384 471	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
PDG	96	PR D54 1		
ABREU	95S	ZPHY C68 375	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	95K	PL B353 402	+Alexander, Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	95L	PL B357 685	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABE	93B	PR D47 R2639	+Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
BUSKULIC	92E	PL B294 145	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
ALBAJAR	91E	PL B273 540	+Albrow, Allkofer, Ankoviak+	(UA1 Collab.)
BARI	91	NC 104A 1787	+Basile, Bruni, Cara Romeo+	(CERN R422 Collab.)
ARENTON	86	NP B274 707	+Chen, Cormell, Dieterle+	(ARIZ, NDAM, VAND)
BASILE	81	LNC 31 97	+Bonvicini, Romeo+	(CERN R415 Collab.)

Ξ_b^0, Ξ_b^-

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗

OMITTED FROM SUMMARY TABLE

ABREU 95V observe an excess of same-sign $\Xi^\mp \ell^\mp$ events in jets, which they interpret as $\Xi_b \to \Xi^- \ell^- \overline{\nu}_\ell X$. They find that the probability for these events to come from non-b-baryon decays is less than 5×10^{-4} and that Λ_b decays can account for less than 10% of these events.

In the quark model, Ξ_b^0 and Ξ_b^- are an isodoublet (usb, dsb) state; the lowest Ξ_b^0 and Ξ_b^- ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_b MEAN LIFE

This is actually a measurement of the average lifetime of b-baryons that decay to a jet containing a same-sign $\Xi^\mp \ell^\mp$ pair. Presumably the mix is mainly Ξ_b, with some Λ_b.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$1.39^{+0.34}_{-0.28}$ OUR EVALUATION				
$1.35^{+0.37}_{-0.28}\,^{+0.15}_{-0.17}$		BUSKULIC	96T ALEP	Excess $\Xi^- \ell^-$, impact parameters
$1.5\ ^{+0.7}_{-0.4}\ \pm 0.3$	8	ABREU	95V DLPH	Excess $\Xi^- \ell^-$, decay lengths

Ξ_b DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^- \ell^- \overline{\nu}_\ell$anything	seen

Ξ_b BRANCHING RATIOS

$\Gamma(\Xi^- \ell^- \overline{\nu}_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
seen	[1] BUSKULIC	96T ALEP	Excess $\Xi^- \ell^-$ over $\Xi^- \ell^+$
seen	ABREU	95V DLPH	Excess $\Xi^- \ell^-$ over $\Xi^- \ell^+$

[1] BUSKULIC 96T measures [B($b \to \Xi_b$) × B($\Xi_b \to \Xi^- \ell^- \overline{\nu}_\ell$anything)] = (5.4 ± 1.1 ± 0.8) × 10^{-4} per lepton species, averaged over e and μ.

Ξ_b REFERENCES

BUSKULIC	96T	PL B384 449	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABREU	95V	ZPHY C68 541	+Adam, Adye, Agasi+	(DELPHI Collab.)

b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b)

b-baryon ADMIXTURE MEAN LIFE

Each measurement of the b-baryon mean life is an average over an admixture of various b baryons which decay weakly. Different techniques emphasize different admixtures of produced particles, which could result in a different b-baryon mean life.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of these Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.20±0.07 OUR EVALUATION				
$1.20 \pm 0.08 \pm 0.06$		[1] BARATE	98D ALEP	$e^+ e^- \to Z$
$1.46^{+0.22}_{-0.21}\,^{+0.07}_{-0.09}$		ABREU	96D DLPH	Excess $\Lambda \ell^- \pi^+$, decay lengths
$1.10^{+0.19}_{-0.17} \pm 0.09$		ABREU	96D DLPH	Excess $\Lambda \mu^-$ impact parameters
$1.16 \pm 0.11 \pm 0.06$		AKERS	96 OPAL	Excess $\Lambda \ell^-$, decay lengths and impact parameters
$1.27^{+0.35}_{-0.29} \pm 0.09$		ABREU	95S DLPH	Excess $p \mu^-$, decay lengths

• • • We do not use the following data for averages, fits, limits, etc. • • •

$1.25\pm0.11\pm0.05$		[2] ABREU	96D DLPH	Combined result
$1.05^{+0.12}_{-0.11}\pm0.09$	290	BUSKULIC	95L ALEP	Repl. by BARATE 98D
$1.04^{+0.48}_{-0.38}\pm0.10$	11	[3] ABREU	93F DLPH	Excess $\Lambda\mu^-$, decay lengths
$1.05^{+0.23}_{-0.20}\pm0.08$	157	[4] AKERS	93 OPAL	Excess $\Lambda\ell^-$, decay lengths
$1.12^{+0.32}_{-0.29}\pm0.16$	101	[5] BUSKULIC	92I ALEP	Excess $\Lambda\ell^-$, impact parameters

[1] Measured using the excess of $\Lambda\ell^-$, lepton impact parameter.

[2] Combined result of the three ABREU 96D methods and ABREU 95S.

[3] ABREU 93F superseded by ABREU 96D.

[4] AKERS 93 superseded by AKERS 96.

[5] BUSKULIC 92I superseded by BUSKULIC 95L.

b-baryon ADMIXTURE (Λ_b,Ξ_b,Σ_b,Ω_b)

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction B($b \rightarrow \Lambda_b$) and are evaluated for our value B($b \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1})$%.

The branching fractions B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) and B($\Lambda_b^0 \rightarrow \Lambda_c^+\ell^-\overline{\nu}_\ell$anything) are not pure measurements because the underlying measured products of these with B($b \rightarrow \Lambda_b$) were used to determine B($b \rightarrow \Lambda_b$), as described in the note "Production and Decay of b-Flavored Hadrons."

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\mu^-\overline{\nu}$anything	(4.9 ± 2.4) %
Γ_2	$\Lambda\ell^-\overline{\nu}_\ell$anything	$(3.1^{+1.0}_{-1.2})$ %
Γ_3	$\Lambda\ell^+\nu_\ell$anything	
Γ_4	Λanything	
Γ_5	$\Lambda_c^+\ell^-\overline{\nu}_\ell$anything	
Γ_6	$\Lambda/\overline{\Lambda}$anything	$(35\ ^{+12}_{-14})$ %
Γ_7	$\Xi^-\ell^-\overline{\nu}_\ell$anything	$(5.5^{+2.0}_{-2.4}) \times 10^{-3}$

b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b) BRANCHING RATIOS

$\Gamma(p\mu^-\overline{\nu}\text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.049^{+0.018+0.015}_{-0.015-0.019}}$	125	[6] ABREU	95S DLPH	$e^+e^- \rightarrow Z$

[6] ABREU 95S reports [B(b-baryon $\rightarrow p\mu^-\overline{\nu}$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.0049 \pm 0.0011^{+0.0015}_{-0.0011}$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\Lambda\ell^-\overline{\nu}_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_2/Γ

The values and averages in this section serve only to show what values result if one assumes our B($b \rightarrow \Lambda_b$). They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine B($b \rightarrow \Lambda_b$) as described in the note on "Production and Decay of b-Flavored Hadrons."

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.031^{+0.010}_{-0.012}}$ **OUR AVERAGE**				
$0.032\pm0.004^{+0.010}_{-0.012}$		[7] BARATE	98D ALEP	$e^+e^- \rightarrow Z$
$0.029\pm0.003^{+0.009}_{-0.011}$		[8] AKERS	96 OPAL	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
$0.030\pm0.007^{+0.009}_{-0.011}$	262	[9] ABREU	95S DLPH	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
$0.060\pm0.012^{+0.019}_{-0.023}$	290	[10] BUSKULIC	95L ALEP	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	157	[11] AKERS	93 OPAL	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
$0.069\pm0.020^{+0.021}_{-0.027}$	101	[12] BUSKULIC	92I ALEP	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$

[7] BARATE 98D reports [B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.00326 \pm 0.00016 \pm 0.00039$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Measured using the excess of $\Lambda\ell^-$, lepton impact parameter.

[8] AKERS 96 reports [B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.00291 \pm 0.00023 \pm 0.00025$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[9] ABREU 95S reports [B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.0030 \pm 0.0006 \pm 0.0004$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[10] BUSKULIC 95L reports [B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.0061 \pm 0.0006 \pm 0.0010$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[11] AKERS 93 superseded by AKERS 96.

[12] BUSKULIC 92I reports [B(b-baryon $\rightarrow \Lambda\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.0070 \pm 0.0010 \pm 0.0018$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Superseded by BUSKULIC 95L.

$\Gamma(\Lambda\ell^+\nu_\ell\text{anything})/\Gamma(\Lambda\text{anything})$ Γ_3/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.070\pm0.012\pm0.007}$	ACKERSTAFF	97N OPAL	$e^+e^- \rightarrow Z$

$\Gamma(\Lambda/\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.35^{+0.12}_{-0.14}}$ **OUR AVERAGE**			
$0.39\pm0.06^{+0.12}_{-0.15}$	[13] ACKERSTAFF	97N OPAL	$e^+e^- \rightarrow Z$
$0.22^{+0.12+0.07}_{-0.08-0.09}$	[14] ABREU	95C DLPH	$e^+e^- \rightarrow Z$

[13] ACKERSTAFF 97N reports [B(b-baryon $\rightarrow \Lambda/\overline{\Lambda}$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.0393 \pm 0.0046 \pm 0.0037$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[14] ABREU 95C reports $0.28^{+0.17}_{-0.12}$ for B($\overline{b} \rightarrow \Lambda_b$) = 0.08 ± 0.02. We rescale to our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\Xi^-\ell^-\overline{\nu}_\ell\text{anything})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0055^{+0.0020}_{-0.0024}}$ **OUR AVERAGE**			
$0.0053\pm0.0013^{+0.0016}_{-0.0021}$	[15] BUSKULIC	96T ALEP	Excess $\Xi^-\ell^-$ over $\Xi^-\ell^+$
$0.0058\pm0.0023^{+0.0018}_{-0.0023}$	[16] ABREU	95V DLPH	Excess $\Xi^-\ell^-$ over $\Xi^-\ell^+$

[15] BUSKULIC 96T reports [B(b-baryon $\rightarrow \Xi^-\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.00054 \pm 0.00011 \pm 0.00008$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[16] ABREU 95V reports [B(b-baryon $\rightarrow \Xi^-\ell^-\overline{\nu}_\ell$anything) × B($\overline{b} \rightarrow \Lambda_b$)] = $0.00059 \pm 0.00021 \pm 0.0001$. We divide by our best value B($\overline{b} \rightarrow \Lambda_b$) = $(10.1^{+3.9}_{-3.1}) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b) REFERENCES

BARATE	98D	EPJ C2 197	R. Barate+	(ALEPH Collab.)
ACKERSTAFF	97N	ZPHY C74 423	K. Ackerstaff+	(OPAL Collab.)
ABREU	96D	ZPHY C71 199	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	96	ZPHY C69 195	+Alexander, Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	96T	PL B384 449	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABREU	95C	PL B347 447	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95S	ZPHY C68 375	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95V	ZPHY C68 541	+Adam, Adye, Agasi+	(DELPHI Collab.)
BUSKULIC	95L	PL B357 685	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABREU	93F	PL B311 379	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	93	PL B316 435	+Alexander, Allison, Anderson+	(OPAL Collab.)
BUSKULIC	92I	PL B297 449	+Decamp, Goy, Lees+	(ALEPH Collab.)

SEARCHES*

Notes in the Search Listings

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* See the Boson Particle Listings for searches for Higgs bosons, other heavy bosons, and axions and other very light bosons; the Lepton Particle Listings for searches for heavy leptons and for neutrino mixing; the Quark Particle Listings for free quark searches; and the Meson Particle Listings for searches for top and fourth-generation hadrons.

SEARCHES FOR MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc.

Magnetic Monopole Searches

MAGNETIC MONOPOLE SEARCHES

Revised December 1997 by D.E. Groom (LBNL).

"At the present time (1975) there is no experimental evidence for the existence of magnetic charges or monopoles, but chiefly because of an early, brilliant theoretical argument by Dirac, the search for monopoles is renewed whenever a new energy region is opened up in high energy physics or a new source of matter, such as rocks from the moon, becomes available [1]." Dirac argued that a monopole anywhere in the universe results in electric charge quantization everywhere, and leads to the prediction of at least magnetic charge $g = e/2\alpha$, the Dirac charge [2]. Recently monopoles have become indispensable in many gauge theories, which endow them with a variety of extraordinarily large masses. The discovery by a candidate event in a single superconducting loop in 1982 [6] stimulated an enormous experimental effort to search for supermassive magnetic monopoles [3,4,5].

Monopole detectors have predominantly used either induction or ionization. Induction experiments measure the monopole magnetic charge and are independent of monopole electric charge, mass, and velocity. Monopole candidate events in single semiconductor loops [6,7] have been detected by this method, but no two-loop coincidence has been observed. Ionization experiments rely on a magnetic charge producing more ionization than an electrical charge with the same velocity. In the case of supermassive monopoles, time-of-flight measurements indicating $v \ll c$ has also been a frequently sought signature.

Cosmic rays are the most likely source of massive monopoles, since accelerator energies are insufficient to produce them. Evidence for such monopoles may also be obtained from astrophysical observations.

Jackson's 1975 assessment remains true. The search is somewhat abated by the lack of success in the 1980's and the decrease of interest in grand unified gauge theories.

References

1. J. D. Jackson, *Classical Electrodynamics*, 2nd edition (John Wiley & Sons, New York, 1975).
2. P.A.M. Dirac, Proc. Royal Soc. London **A133**, 60 (1931).
3. J. Preskill, Ann. Rev. Nucl. and Part. Sci. **34**, 461 (1984).
4. G. Giacomelli, La Rivista del Nuovo Cimento **7**, N. 12, 1 (1984).
5. Phys. Rep. **140**, 323 (1986).
6. B. Cabrera, Phys. Rev. Lett. **48**, 1378 (1982) .
7. A.D. Caplin *et al.*, Nature **321**, 402 (1986) .

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	*MASS* (GeV)	*CHG* (g)	*ENERGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<0.65E−33	<3.3	≥ 2	11*A*	^{197}Au	0	[1] HE	97	
<1.90E−33	<8.1	≥ 2	160*A*	^{208}Pb	0	[1] HE	97	
<3.E−37	<45.0	1.0	88–94	e^+e^-	0	PINFOLD	93	PLAS
<3.E−37	<41.6	2.0	88–94	e^+e^-	0	PINFOLD	93	PLAS
<7.E−35	<44.9	0.2–1.0	89–93	e^+e^-	0	KINOSHITA	92	PLAS
<2.E−34	<850	≥ 0.5	1800	$p\overline{p}$	0	BERTANI	90	PLAS
<1.2E−33	<800	≥ 1	1800	$p\overline{p}$	0	PRICE	90	PLAS
<1.E−37	<29	1	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−37	<18	2	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−38	<17	<1	35	e^+e^-	0	BRAUNSCH...	88B	CNTR
<8.E−37	<24	1	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<1.3E−35	<22	2	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<9.E−37	<4	<0.15	10.6	e^+e^-	0	GENTILE	87	CLEO
<3.E−32	<800	≥ 1	1800	$p\overline{p}$	0	PRICE	87	PLAS
<3.E−38		<3	29	e^+e^-	0	FRYBERGER	84	PLAS
<1.E−31		1,3	540	$p\overline{p}$	0	AUBERT	83B	PLAS
<4.E−38	<10	<6	34	e^+e^-	0	MUSSET	83	PLAS
<8.E−36	<20		52	pp	0	[2] DELL	82	CNTR
<9.E−37	<30	<3	29	e^+e^-	0	KINOSHITA	82	PLAS
<1.E−37	<20	<24	63	pp	0	CARRIGAN	78	CNTR
<1.E−37	<30	<3	56	pp	0	HOFFMANN	78	PLAS
			62	pp	0	[2] DELL	76	SPRK
<4.E−33			300	p	0	[2] STEVENS	76B	SPRK
<1.E−40	<5	<2	70	p	0	[3] ZRELOV	76	CNTR
<2.E−30			300	n	0	[2] BURKE	75	OSPK
<1.E−38			8	ν	0	[4] CARRIGAN	75	HLBC
<5.E−43	<12	<10	400	p	0	EBERHARD	75B	INDU
<2.E−36	<30	<3	60	pp	0	GIACOMELLI	75	PLAS
<5.E−42	<13	<24	400	p	0	CARRIGAN	74	CNTR
<6.E−42	<12	<24	300	p	0	CARRIGAN	73	CNTR
<2.E−36		1	0.001	γ	0	[3] BARTLETT	72	CNTR
<1.E−41	<5		70	p	0	GUREVICH	72	EMUL
<1.E−40	<3	<2	28	p	0	AMALDI	63	EMUL
<2.E−40	<3	<2	30	p	0	PURCELL	63	CNTR
<1.E−35	<3	<4	28	p	0	FIDECARO	61	CNTR
<2.E−35	<1	1	6	p	0	BRADNER	59	EMUL

[1] HE 97 used a lead target and barium phosphate glass detectors. Cross-section limits are well below those predicted via the Drell-Yan mechanism.

[2] Multiphoton events.

[3] Cherenkov radiation polarization.

[4] Re-examines CERN neutrino experiments.

Monopole Production — Other Accelerator Searches

MASS (GeV)	*CHG* (g)	*ENERGY* (GeV)	*BEAM*	*DOCUMENT ID*		*TECN*
>510		88–94	e^+e^-	[5] ACCIARRI	95C	L3

[5] ACCIARRI 95C finds a limit B($Z \rightarrow \gamma\gamma\gamma$) $< 0.8 \times 10^{-5}$ (which is possible via a monopole loop) at 95% CL and sets the mass limit via a cross section model.

Monopole Flux — Cosmic Ray Searches

FLUX (cm^{-2}sr^{-1}s^{-1})	*MASS* (GeV)	*CHG* (g)	*COMMENTS* ($\beta = v/c$)	*EVTS*	*DOCUMENT ID*		*TECN*
<1E−15		**1**	**1.1×10^{-4}–0.1**	0	[6] AMBROSIO	97	MCRO
<4.1E−15		1	(0.18–2.7)E−3	0	[7] AMBROSIO	97	MCRO
<1.0E−15		1	0.0012–0.1	0	[8] AMBROSIO	97	MCRO
<0.87E−15			(0.11–5)E−3	0	[9] AMBROSIO	97	MCRO
<6.8E−15		1	4.0E−5	0	[10] AMBROSIO	97	MCRO
<2.8E−15		1	0.1–1	0	[11] AMBROSIO	97	MCRO
<4.4E−15		1	0.1–1	0	[12] AMBROSIO	97	MCRO
<5.6E−15		1	(0.18–3.0)E−3	0	[13] AHLEN	94	MCRO
<2.7E−15		1	$\beta \sim 1 \times 10^{-3}$	0	[14] BECKER-SZ...	94	IMB
<8.7E−15		1	>2.E−3	0	THRON	92	SOUD
<4.4E−12		1	all β	0	GARDNER	91	INDU
<7.2E−13		1	all β	0	HUBER	91	INDU
<3.7E−15	>E12	1	β=1.E−4	0	[15] ORITO	91	PLAS
<3.2E−16	>E10	1	$\beta > 0.05$	0	[15] ORITO	91	PLAS
<3.2E−16	>E10–E12	2, 3		0	[15] ORITO	91	PLAS
<3.8E−13		1	all β	0	BERMON	90	INDU
<5.E−16		1	β <1.E−3	0	[14] BEZRUKOV	90	CHER
<1.8E−14		1	β >1.1E−4	0	[16] BUCKLAND	90	HEPT
<1E−18			3.E−4 < β <1.5E−3	0	[17] GHOSH	90	MICA
<7.2E−13		1	all β	0	HUBER	90	INDU
<5.E−12	>E7	1	3.E−4 < β <5.E−3	0	BARISH	87	CNTR
<1.E−13			1.E−5 < β <1	0	[14] BARTELT	87	SOUD
<1.E−10		1	all β	0	EBISU	87	INDU
<2.E−13			1.E−4 < β <6.E−4	0	MASEK	87	HEPT
<2.E−14			4.E−5 < β <2.E−4	0	NAKAMURA	87	PLAS
<2.E−14			1.E−3 < β <1	0	NAKAMURA	87	PLAS
<5.E−14			9.E−4 < β <1.E−2	0	SHEPKO	87	CNTR
<2.E−13			4.E−4 < β <1	0	TSUKAMOTO	87	CNTR
<5.E−14		1	all β	1	[18] CAPLIN	86	INDU
<5.E−12		1		0	CROMAR	86	INDU
<1.E−13		1	7.E−4 < β	0	HARA	86	CNTR

<7.E−11		1	all β	0	INCANDELA 86	INDU
<1.E−18			$4.E-4 < \beta < 1.E-3$	0	[17] PRICE 86	MICA
<5.E−12		1		0	BERMON 85	INDU
<6.E−12		1		0	CAPLIN 85	INDU
<6.E−10		1		0	EBISU 85	INDU
<3.E−15			$5.E-5 \le \beta \le 1.E-3$	0	[14] KAJITA 85	KAMI
<2.E−21			$\beta < 1.E-3$	0	[14,19] KAJITA 85	KAMI
<3.E−15			$1.E-3 < \beta < 1.E-1$	0	[14] PARK 85B	CNTR
<5.E−12		1	$1.E-4 < \beta < 1$	0	BATTISTONI 84	NUSX
<7.E−12		1		0	INCANDELA 84	INDU
<7.E−13		1	$3.E-4 < \beta$	0	[16] KAJINO 84	CNTR
<2.E−12		1	$3.E-4 < \beta < 1.E-1$	0	KAJINO 84B	CNTR
<6.E−13		1	$5.E-4 < \beta < 1$	0	KAWAGOE 84	CNTR
<2.E−14			$1.E-3 < \beta$	0	[14] KRISHNA... 84	CNTR
<4.E−13		1	$6.E-4 < \beta < 2.E-3$	0	LISS 84	CNTR
<1.E−16			$3.E-4 < \beta < 1.E-3$	0	[17] PRICE 84	MICA
<1.E−13		1	$1.E-4 < \beta$	0	PRICE 84B	PLAS
<4.E−13		1	$6.E-4 < \beta < 2.E-3$	0	TARLE 84	CNTR
				7	[20] ANDERSON 83	EMUL
<4.E−13		1	$1.E-2 < \beta < 1.E-3$	0	BARTELT 83B	CNTR
<1.E−12		1	$7.E-3 < \beta < 1$	0	BARWICK 83	PLAS
<3.E−13		1	$1.E-3 < \beta < 4.E-1$	0	BONARELLI 83	CNTR
<3.E−12			$5.E-4 < \beta < 5.E-2$	0	[14] BOSETTI 83	CNTR
<4.E−11		1		0	CABRERA 83	INDU
<5.E−15		1	$1.E-2 < \beta < 1$	0	DOKE 83	PLAS
<8.E−15			$1.E-4 < \beta < 1.E-1$	0	[14] ERREDE 83	IMB
<5.E−12		1	$1.E-4 < \beta < 3.E-2$	0	GROOM 83	CNTR
<2.E−12			$6.E-4 < \beta < 1$	0	MASHIMO 83	CNTR
<1.E−13		1	β=3.E−3	0	ALEXEYEV 82	CNTR
<2.E−12		1	$7.E-3 < \beta < 6.E-1$	0	BONARELLI 82	CNTR
6.E−10		1	all β	1	[21] CABRERA 82	INDU
<2.E−11			$1.E-2 < \beta < 1.E-1$	0	MASHIMO 82	CNTR
<2.E−15			concentrator	0	BARTLETT 81	PLAS
<1.E−13	>1		$1.E-3 < \beta$	0	KINOSHITA 81B	PLAS
<5.E−11	<E17		$3.E-4 < \beta < 1.E-3$	0	ULLMAN 81	CNTR
<2.E−11			concentrator	0	BARTLETT 78	PLAS
1.E−1	>200	2		1	[22] PRICE 75	PLAS
<2.E−13		>2		0	FLEISCHER 71	PLAS
<1.E−19		>2	obsidian, mica	0	FLEISCHER 69C	PLAS
<5.E−15	<15	<3	concentrator	0	CARITHERS 66	ELEC
<2.E−11		<1−3	concentrator	0	MALKUS 51	EMUL

[6] AMBROSIO 97 global MACRO 90%CL is 0.78×10^{-15} at $\beta=1.1 \times 10^{-4}$, goes through a minimum at 0.61×10^{-15} near $\beta=(1.1\text{–}2.7) \times 10^{-3}$, then rises to 0.84×10^{-15} at $\beta=0.1$. The global limit in this region is below the Parker bound at 10^{-15}. Less stringent limits are established for $4 \times 10^{-5} < \beta < 1$. Limits set by various triggers in the detector are listed below. All limits assume a catalysis cross section smaller than 10 mb.

[7] AMBROSIO 97 "Scintillator D" (low velocity) 90%CL increases from 4.1×10^{-15} at $\beta=2.7 \times 10^{-3}$ to 14.6×10^{-15} at $\beta=0.006$.

[8] AMBROSIO 97 "Scintillator B" 90%CL (single medium-velocity trigger with two analysis criteria).

[9] AMBROSIO 97 streamer tube 90%CL. Tubes contain helium, and hence trigger is sensitive via the atomic induction mechanism.

[10] AMBROSIO 97 CR39 90%CL improves to 4.3×10^{-15} at $\beta=1.0 \times 10^{-4}$. CR39 is sensitive for $4 \times 10^{-5} < \beta < 1$ except for a window at $0.25 \times 10^{-3} < \beta < 2.1 \times 10^{-3}$. In the middle region other triggers set better limits.

[11] AMBROSIO 97 CR39 90%CL falls to 2.7×10^{-15} at $\beta=1$ and increases at lower velocities. Provides better limit than "Scintillator C" for $0.1 < \beta < 1.0$.

[12] AMBROSIO 97 "Scintillator C" 90%CL, based on high absolute energy loss in two scintillator layers.

[13] AHLEN 94 limit for dyons extends down to β=0.9E−4 and a limit of 1.3E−14 extends to β = 0.8E−4. Also see comment by PRICE 94 and reply of BARISH 94. One loophole in the AHLEN 94 result is that in the case of monopoles catalyzing nucleon decay, relativisitic particles could veto the events. See AMBROSIO 97 for additional results.

[14] Catalysis of nucleon decay; sensitive to assumed catalysis cross section.

[15] ORITO 91 limits are functions of velocity. Lowest limits are given here.

[16] Used DKMPR mechanism and Penning effect.

[17] Assumes monopole attaches fermion nucleus.

[18] Limit from combining data of CAPLIN 86, BERMON 85, INCANDELA 84, and CABRERA 83. For a discussion of controversy about CAPLIN 86 observed event, see GUY 87. Also see SCHOUTEN 87.

[19] Based on lack of high- energy solar neutrinos from catalysis in the sun.

[20] Anomalous long-range α (^{4}He) tracks.

[21] CABRERA 82 candidate event has single Dirac charge within ±5%.

[22] ALVAREZ 75, FLEISCHER 75, and FRIEDLANDER 75 explain as fragmenting nucleus. EBERHARD 75 and ROSS 76 discuss conflict with other experiments. HAGSTROM 77 reinterprets as antinucleus. PRICE 78 reassesses.

Monopole Flux — Astrophysics

FLUX ($\mathrm{cm^{-2} sr^{-1} s^{-1}}$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID	TECN
<1.E−16	E17	1	galactic field	0	[23] ADAMS 93	COSM
<1.E−23			Jovian planets		[24] ARAFUNE 85	COSM
<1.E−16	E15		solar trapping	0	BRACCI 85B	COSM
<1.E−18		1		0	[24] HARVEY 84	COSM
<3.E−23			neutron stars		KOLB 84	COSM
<7.E−22			pulsars	0	[24] FREESE 83B	COSM
<1.E−18	<E18	1	intergalactic field	0	[24] REPHAELI 83	COSM
<1.E−23			neutron stars	0	[24] DIMOPOUL... 82	COSM
<5.E−22			neutron stars	0	[24] KOLB 82	COSM
<5.E−15	>E21		galactic halo		SALPETER 82	COSM
<1.E−12	E19	1	β=3.E−3	0	[25] TURNER 82	COSM
<1.E−16		1	galactic field	0	PARKER 70	COSM

[23] ADAMS 93 limit based on "survival and growth of a small galactic seed field" is 10^{-16} $(m/10^{17}\ \mathrm{GeV})\ \mathrm{cm^{-2} s^{-1} sr^{-1}}$. Above 10^{17} GeV, limit 10^{-16} $(10^{17}\ \mathrm{GeV}/m)\ \mathrm{cm^{-2} s^{-1} sr^{-1}}$ (from requirement that monopole density does not overclose the universe) is more stringent.

[24] Catalysis of nucleon decay.

[25] Re-evaluates PARKER 70 limit for GUT monopoles.

Monopole Density — Matter Searches

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID	TECN
<6.9E−6/gram	>1/3	Meteorites and other	0	JEON 95	INDU
<2.E−7/gram	>0.6	Fe ore	0	[26] EBISU 87	INDU
<4.6E−6/gram	> 0.5	deep schist	0	KOVALIK 86	INDU
<1.6E−6/gram	> 0.5	manganese nodules	0	[27] KOVALIK 86	INDU
<1.3E−6/gram	> 0.5	seawater	0	KOVALIK 86	INDU
>1.E+14/gram	>1/3	iron aerosols	>1	MIKHAILOV 83	SPEC
<6.E−4/gram		air, seawater	0	CARRIGAN 76	CNTR
<5.E−1/gram	>0.04	11 materials	0	CABRERA 75	INDU
<2.E−4/gram	>0.05	moon rock	0	ROSS 73	INDU
<6.E−7/gram	<140	seawater	0	KOLM 71	CNTR
<1.E−2/gram	<120	manganese nodules	0	FLEISCHER 69	PLAS
<1.E−4/gram	>0	manganese	0	FLEISCHER 69B	PLAS
<2.E−3/gram	<1−3	magnetite, meteor	0	GOTO 63	EMUL
<2.E−2/gram		meteorite	0	PETUKHOV 63	CNTR

[26] Mass 1×10^{14}–1×10^{17} GeV.

[27] KOVALIK 86 examined 498 kg of schist from two sites which exhibited clear minearalogic evidence of halvng been buried at least 20 km deep and held below the Curie temperature.

Monopole Density — Astrophysics

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID	TECN
<1.E−9/gram	1	sun, catalysis	0	[28] ARAFUNE 83	COSM
<6.E−33/nucl	1	moon wake	0	SCHATTEN 83	ELEC
<2.E−28/nucl		earth heat	0	CARRIGAN 80	COSM
<2.E−4/prot		42cm absorption	0	BRODERICK 79	COSM
<2.E−13/$\mathrm{m^3}$		moon wake	0	SCHATTEN 70	ELEC

[28] Catalysis of nucleon decay.

REFERENCES FOR Magnetic Monopole Searches

AMBROSIO 97 PL B406 249 M. Ambrosio+ (MACRO Collab.)
HE 97 PRL 79 3134 Y.D. He (UCB)
ACCIARRI 95C PL B345 609 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
JEON 95 PRL 75 1443 Jeon, Longo (MICH)
Also 96 PRL 76 159 (errata)
AHLEN 94 PRL 72 608 +Ambrosio, Antolini, Auriemma+ (MACRO Collab.)
BARISH 94 PRL 73 1306 +Giacomelli, Hong (CIT, BGNA, BOST)
BECKER-SZ... 94 PR D49 2169 Becker-Szendy, Bratton, Breault, Casper+ (IMB Collab.)
PRICE 94 PRL 73 1305 (UCB)
ADAMS 93 PRL 70 2511 +Fatuzzo, Freese, Tarle+ (MICH, FNAL)
PINFOLD 93 PL B316 407 +Du, Kinoshita, Lorazo+ (ALBE, HARV, MONT, UCB)
KINOSHITA 92 PR D46 R881 +Du, Giacomelli, Patriziili+ (HARV, BGNA, REHO)
THRON 92 PR D46 4846 +Allison, Alner, Ambats+ (SOUDAN-2 Collab.)
GARDNER 91 PR D44 622 +Cabrera, Huber, Taber (STAN)
HUBER 91 PR D44 636 +Cabrera, Taber, Gardner (STAN)
ORITO 91 PRL 66 1951 +Ichinose, Nakamura+ (ICEPP, WASCR, NIHO, ICRR)
BERMON 90 PRL 64 839 +Chi, Tsuei+ (IBM, BNL)
BERTANI 90 EPL 12 613 +Giacomelli, Mondardini, Pal+ (BGNA, INFN)
BEZRUKOV 90 SJNP 52 54 +Belolaptikov, Bugaev, Budnev+ (INRM)
Translated from YAF 52 86.
BUCKLAND 90 PR D41 2726 +Masek, Vernon, Knapp, Stronsi (UCSD)
GHOSH 90 EPL 12 25 +Chatterjea (JADA)
HUBER 90 PRL 64 835 +Cabrera, Tabor, Gardner (STAN)
PRICE 90 PRL 65 149 +Guiru, Kinoshita (UCB, HARV)
KINOSHITA 89 PL B228 543 +Fujii, Nakajima+ (HARV, TISA, KEK, UCB, GIFU)
BRAUNSCH... 88B ZPHY C38 543 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
KINOSHITA 88 PRL 60 1610 +Fujii, Nakajima+ (HARV, TISA, KEK, UCB, GIFU)
BARISH 87 PR D36 2641 +Liu, Lane (CIT)
BARTELT 87 PR D36 1990 +Courant, Heller+ (Soudan Collab.)
Also 89 PR D40 1701 erratum Bartelt, Courant, Heller+ (Soudan Collab.)
EBISU 87 PR D36 3359 +Watanabe (KOBE)
Also 85 JPG 11 883 Ebisu, Watanabe (KOBE)
GENTILE 87 PR D35 1081 +Haas, Hempstead+ (CLEO Collab.)
GUY 87 Nature 325 463 (LOIC)
MASEK 87 PR D35 2758 +Knapp, Miller, Stronski, Vernon, White (UCSD)
NAKAMURA 87 PL B183 395 +Kawagoe, Yamamoto+ (INUS, WASCR, NIHO)
PRICE 87 PRL 59 2523 +Guoxiao, Kinoshita (UCB, HARV)
SCHOUTEN 87 JPE 20 850 +Caplin, Guy, Hardiman+ (LOIC)
SHEPKO 87 PR D35 2917 +Gagliardi, Green, McIntyre+ (TAMU)
TSUKAMOTO 87 EPL 3 39 +Nagano, Anraku+ (ICRR)
CAPLIN 86 Nature 321 402 +Hardiman, Koratzinos, Schouten (LOIC)
Also 87 JPE 20 850 Schouten, Caplin, Guy, Hardiman+ (LOIC)
Also 87 Nature 325 463 Guy (LOIC)
CROMAR 86 PRL 56 2561 +Clark, Fickett (NBSB)
HARA 86 PRL 56 553 +Honda, Ohno+ (ICRR, KYOT, KEK, KOBE, ICEPP)
INCANDELA 86 PR D34 2637 +Frisch, Somalwar, Kuchnir+ (CHIC, FNAL, MICH)
KOVALIK 86 PR A33 1183 J.M. Kovalik, J.L. Kirschvink (CIT)
PRICE 86 PRL 56 1226 +Salamon (UCB)
ARAFUNE 85 PR D32 2586 +Fukugita, Yanagita (ICRR, KYOTU, IBAR)
BERMON 85 PRL 55 1850 +Chaudhari, Chi, Tesche, Tsuei (IBM)
BRACCI 85B NP B258 726 +Fiorentini, Mezzorani (PISA, CAGL, INFN)
Also 85 LNC 42 123 Bracci, Fiorentini (PISA)
CAPLIN 85 Nature 317 234 +Guy, Hardiman, Park, Schouten (LOIC)
EBISU 85 JPG 11 883 +Watanabe (KOBE)
KAJITA 85 JPSJ 54 4065 +Arisaka, Koshiba, Nakahata+ (ICRR, KEK, NIIG)
PARK 85B NP B252 261 +Blewitt, Cortez, Foster+ (IMB Collab.)
BATTISTONI 84 PL 133B 454 +Bellotti, Bologna, Campana+ (NUSEX Collab.)

FRYBERGER	84	PR D29 1524	+Coan, Kinoshita, Price	(SLAC, UCB)
HARVEY	84	NP B236 255		(PRIN)
INCANDELA	84	PRL 53 2067	+Campbell, Frisch+	(CHIC, FNAL, MICH)
KAJINO	84	PRL 52 1373	+Matsuno, Yuan, Kitamura	(ICRR)
KAJINO	84B	JPG 10 447	+Matsuno, Kitamura, Aoki, Yuan, Mitsui+	(ICRR)
KAWAGOE	84	LNC 41 315	+Mashimo, Nakamura, Nozaki, Orito	(TOKY)
KOLB	84	APJ 286 702	+Turner	(FNAL, CHIC)
KRISHNA...	84	PL 142B 99	Krishnaswamy, Menon+	(TATA, OSKC, INUS)
LISS	84	PR D30 884	+Ahlen, Tarle	(UCB, IND, MICH)
PRICE	84	PRL 52 1265	+Guo, Ahlen, Fleischer	(ROMA, UCB, IND, GESC)
PRICE	84B	PL 140B 112		(CERN)
TARLE	84	PRL 52 90	+Ahlen, Liss	(UCB, MICH, IND)
ANDERSON	83	PR D28 2308	+Lord, Strausz, Wilkes	(WASH)
ARAFUNE	83	PL 133B 380	+Fukugita	(ICRR, KYOTU)
AUBERT	83B	PL 120B 465	+Musset, Price, Vialle	(CERN, LAPP)
BARTELT	83B	PRL 50 655	+Courant, Heller, Joyce, Marshak+	(MINN, ANL)
BARWICK	83	PR D28 2338	+Kinoshita, Price	(UCB)
BONARELLI	83	PL 126B 137	+Capiluppi, Dantone	(BGNA)
BOSETTI	83	PL 133B 265	+Gorham, Harris, Learned+	(AACH3, HAWA, TOKY)
CABRERA	83	PRL 51 1933	+Taber, Gardner, Bourg	(STAN)
DOKE	83	PL 129B 370	+Hayashi, Hamasaki+	(WASU, RIKK, TTAM, RIKEN)
ERREDE	83	PRL 51 245	+Stone, Vander Velde, Bionta+	(IMB Collab.)
FREESE	83B	PRL 51 1625	+Turner, Schramm	(CHIC)
GROOM	83	PRL 50 573	+Loh, Nelson, Ritson	(UTAH, STAN)
MASHIMO	83	PL 128B 327	+Orito, Kawagoe, Nakamura, Nozaki	(ICEPP)
MIKHAILOV	83	PL 130B 331		(KAZA)
MUSSET	83	PL 128B 333	+Price, Lohrmann	(CERN, HAMB)
REPHAELI	83	PL 121B 115	+Turner	(CHIC)
SCHATTEN	83	PR D27 1525		(NASA)
ALEXEYEV	82	LNC 35 413	+Boliev, Chudakov, Makoev, Mikheyev+	(INRM)
BONARELLI	82	PL 112B 100	+Capiluppi, Dantone+	(BGNA)
CABRERA	82	PRL 48 1378		(STAN)
DELL	82	NP B209 45	+Yuan, Roberts, Dooher+	(BNL, ADEL, ROMA)
DIMOPOUL...	82	PL 119B 320	Dimopoulos, Preskill, Wilczek	(HARV, UCSBT)
KINOSHITA	82	PRL 48 77	+Price, Fryberger	(UCB, SLAC)
KOLB	82	PRL 49 1373	+Colgate, Harvey	(LASL, PRIN)
MASHIMO	82	JPSJ 51 3067	+Kawagoe, Koshiba	(INUS)
SALPETER	82	PRL 49 1114	+Shapiro, Wasserman	(CORN)
TURNER	82	PR D26 1296	+Parker, Bogdan	(CHIC)
BARTLETT	81	PR D24 612	+Soo, Fleischer, Hart+	(COLO, GESC)
KINOSHITA	81B	PR D24 1707	+Price	(UCB)
ULLMAN	81	PRL 47 289		(LEHM, BNL)
CARRIGAN	80	Nature 288 348		(FNAL)
BRODERICK	79	PR D19 1046	+Ficenec, Teplitz, Teplitz	(VPI)
BARTLETT	78	PR D18 2253	+Soo, White	(COLO, PRIN)
CARRIGAN	78	PR D17 1754	+Strauss, Giacomelli	(FNAL, BGNA)
HOFFMANN	78	LNC 23 357	+Kantardjian, Diliberto, Meddi+	(CERN, ROMA)
PRICE	78	PR D18 1382	+Shirk, Osborne, Pinsky	(UCB, HOUS)
HAGSTROM	77	PRL 38 729		(LBL)
CARRIGAN	76	PR D13 1823	+Nezrick, Strauss	(FNAL)
DELL	76	LNC 15 269	+Uto, Yuan, Amaldi+	(CERN, BNL, ROMA, ADEL)
ROSS	76	LBL-4665		(LBL)
STEVENS	76B	PR D14 2207	+Collins, Ficenec, Trower, Fischer+	(VPI, BNL)
ZRELOV	76	CZJP B26 1306	+Kollarova, Kollar, Lupiltsev, Pavlovic+	(JINR)
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BURKE	75	PL 60B 113	+Gustafson, Jones, Longo	(MICH)
CABRERA	75	Thesis		(STAN)
CARRIGAN	75	NP B91 279	+Nezrick	(FNAL)
Also	71	PR D3 56	Carrigan, Nezrick	(FNAL)
EBERHARD	75	PR D11 3099	+Ross, Taylor, Alvarez, Oberlack	(LBL, MPIM)
EBERHARD	75B	LBL-4289		(LBL)
FLEISCHER	75	PRL 35 1412	+Walker	(GESC, WUSL)
FRIEDLANDER	75	PRL 35 1167		(WUSL)
GIACOMELLI	75	NC 28A 21	+Rossi+	(BGNA, CERN, SACL, ROMA)
PRICE	75	PRL 35 487	+Shirk, Osborne, Pinsky	(UCB, HOUS)
CARRIGAN	74	PR D10 3867	+Nezrick, Strauss	(FNAL)
CARRIGAN	73	PR D8 3717	+Nezrick, Strauss	(FNAL)
ROSS	73	PR D8 698	+Eberhard, Alvarez, Watt	(LBL, SLAC)
Also	71	PR D4 3260	Eberhard, Ross, Alvarez, Watt	(LBL, SLAC)
Also	70	Science 167 701	Alvarez, Eberhard, Ross, Watt	(LBL, SLAC)
BARTLETT	72	PR D6 1817	+Lahana	(COLO)
GUREVICH	72	PL 38B 549	+Khakimov, Martemyanov+	(KIAE, NOVO, SERP)
Also	72B	JETP 34 917	Barkov, Gurevich, Zolotorev	(KIAE, NOVO, SERP)
		Translated from ZETF 61 1721.		
Also	70	PL 31B 394	Gurevich, Khakimov+	(KIAE, NOVO, SERP)
FLEISCHER	71	PR D4 24	+Hart, Nichols, Price	(GESC)
KOLM	71	PR D4 1285	+Villa, Odian	(MIT, SLAC)
PARKER	70	APJ 160 383		(CHIC)
SCHATTEN	70	PR D1 2245		(NASA)
FLEISCHER	69	PR 177 2029	+Jacobs, Schwartz, Price	(GESC, FSU)
FLEISCHER	69B	PR 184 1393	+Hart, Jacobs+	(GESC, UNCS, GSCO)
FLEISCHER	69C	PR 184 1398	+Price, Woods	(GESC)
Also	70C	JAP 41 958	Fleischer, Hart, Jacobs, Price+	(GESC)
CARITHERS	66	PR 149 1070	+Stefanski, Adair	(YALE, BNL)
AMALDI	63	NC 28 773	+Baroni, Manfredini+	(ROMA, UCSD, CERN)
GOTO	63	PR 132 387	+Kolm, Ford	(TOKY, MIT, BRAN)
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Supersymmetric Particle Searches

SUPERSYMMETRY

Written October 1997 by Howard E. Haber (Univ. of California, Santa Cruz) Part I, and by M. Schmitt (CERN*) Part II

This review is divided into two parts:

Supersymmetry, Part I (Theory)

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I.2. Structure of the MSSM
I.3. Parameters of the MSSM
I.4. The Higgs sector of the MSSM
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II.6. Supersymmetry searches at HERA and fixed-target experiment
II.7. Conclusions

SUPERSYMMETRY, PART I (THEORY)

(by H.E. Haber)

I.1. Introduction: Supersymmetry (SUSY) is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa. It also provides a framework for the unification of particle physics and gravity [1–3], which is governed by the Planck scale, $M_{\rm P} \approx 10^{19}$ GeV (defined to be the energy scale where the gravitational interactions of elementary particles become comparable to their gauge interactions). If supersymmetry were an exact symmetry of nature, then particles and their superpartners (which differ in spin by half a unit) would be degenerate in mass. Thus, supersymmetry cannot be an exact symmetry of nature, and must be broken. In theories of "low-energy" supersymmetry, the effective scale of supersymmetry breaking is tied to the electroweak scale [4–6], which is characterized by the Standard Model Higgs vacuum expectation value $v = 246$ GeV. It is thus possible that supersymmetry will ultimately explain the origin of the large hierarchy of energy scales from the W and Z masses to the Planck scale.

At present, there are no unambiguous experimental results that require the existence of low-energy supersymmetry. However, if experimentation at future colliders uncovers evidence for supersymmetry, this would have a profound effect on the study of TeV-scale physics and the development of a more fundamental theory of mass and symmetry-breaking phenomena in particle physics.

I.2. Structure of the MSSM: The minimal supersymmetric extension of the Standard Model (MSSM) consists of taking the Standard Model and adding the corresponding supersymmetric partners [7]. In addition, the MSSM contains two hypercharge $Y = \pm 1$ Higgs doublets, which is the minimal structure for the Higgs sector of an anomaly-free supersymmetric extension of the Standard Model. The supersymmetric structure of the theory also requires (at least) two Higgs doublets to generate mass for both "up"-type and "down"-type quarks (and charged leptons) [8,9]. All renormalizable supersymmetric interactions consistent with (global) B–L conservation (B =baryon number and L =lepton number) are included. Finally, the most general soft-supersymmetry-breaking terms are added [10].

If supersymmetry is relevant for explaining the scale of electroweak interactions, then the mass parameters introduced by the soft-supersymmetry-breaking terms must be of order 1 TeV or below [11]. Some bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators [12]. Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [13,14]. The impact of precision electroweak measurements at LEP and SLC on the MSSM parameter space is discussed briefly in Section I.8.

As a consequence of B–L invariance, the MSSM possesses a multiplicative R-parity invariance, where $R = (-1)^{3(B-L)+2S}$ for a particle of spin S [15]. Note that this formula implies that all the ordinary Standard Model particles have even R-parity, whereas the corresponding supersymmetric partners have odd R-parity. The conservation of R-parity in scattering and decay processes has a crucial impact on supersymmetric phenomenology. For example, starting from an initial state involving ordinary (R-even) particles, it follows that supersymmetric particles must be produced in pairs. In general, these particles are highly unstable and decay quickly into lighter states. However, R-parity invariance also implies that the lightest supersymmetric particle (LSP) is absolutely stable, and must eventually be produced at the end of a decay chain initiated by the decay of a heavy unstable supersymmetric particle.

In order to be consistent with cosmological constraints, a stable LSP is almost certainly electrically and color neutral [16]. Consequently, the LSP in a R-parity-conserving theory is weakly-interacting in ordinary matter, *i.e.* it behaves like a stable heavy neutrino and will escape detectors without being directly observed. Thus, the canonical signature for conventional R-parity-conserving supersymmetric theories is missing (transverse) energy, due to the escape of the LSP. Moreover, the LSP is a prime candidate for "cold dark matter", a potentially important component of the non-baryonic dark matter that is required in cosmologies with a critical mass density [17].

In the MSSM, supersymmetry breaking is accomplished by including the most general renormalizable soft-supersymmetry-breaking terms consistent with the SU(3)×SU(2)×U(1) gauge symmetry and R-parity invariance. These terms parameterize our ignorance of the fundamental mechanism of supersymmetry breaking. If supersymmetry breaking occurs spontaneously, then a massless Goldstone fermion called the *goldstino* ($\widetilde{G}$) must exist. The goldstino would then be the LSP and could play an important role in supersymmetric phenomenology [18]. However, the goldstino is a physical degree of freedom only in models of spontaneously broken global supersymmetry. If the supersymmetry is a local symmetry, then the theory must incorporate gravity; the resulting theory is called supergravity. In models of spontaneously broken supergravity, the goldstino is "absorbed" by the *gravitino* ($\widetilde{g}_{3/2}$), the spin-3/2 partner of the graviton [19]. By this super-Higgs mechanism, the goldstino is removed from the physical spectrum and the gravitino acquires a mass ($m_{3/2}$).

It is very difficult (perhaps impossible) to construct a model of spontaneously-broken low-energy supersymmetry where the supersymmetry breaking arises solely as a consequence of the interactions of the particles of the MSSM. A more viable scheme posits a theory consisting of at least two distinct sectors: a "hidden" sector consisting of particles that are completely neutral with respect to the Standard Model gauge group, and a "visible" sector consisting of the particles of the MSSM. There are no renormalizable tree-level interactions between particles of the visible and hidden sectors. Supersymmetry breaking is assumed to occur in the hidden sector, and then transmitted to the MSSM by some mechanism. Two theoretical scenarios have been examined in detail: gravity-mediated and gauge-mediated supersymmetry breaking.

All particles feel the gravitational force. In particular, particles of the hidden sector and the visible sector can interact via the exchange of gravitons. Thus, supergravity models provide a natural mechanism for transmitting the supersymmetry breaking of the hidden sector to the particle spectrum of the MSSM. In models of *gravity-mediated* supersymmetry breaking, gravity is the messenger of supersymmetry breaking [20,21]. In this scenario, the gravitino mass is of order the electroweak-symmetry-breaking scale, while its couplings are roughly gravitational in strength [1,22]. Such a gravitino would play no role in supersymmetric phenomenology at colliders.

In *gauge-mediated* supersymmetry breaking, supersymmetry breaking is transmitted to the MSSM via gauge forces. The canonical structure of such models involves a hidden sector where supersymmetry is broken, a "messenger sector" consisting of particles (messengers) with SU(3)×SU(2)×U(1) quantum numbers, and the visible sector consisting of the fields of the MSSM [23,24]. The direct coupling of the messengers to the hidden sector generates a supersymmetry breaking spectrum in the messenger sector. Finally, supersymmetry breaking is transmitted to the MSSM via the virtual exchange of the messengers. If this approach is extended to incorporate gravitational phenomena, then supergravity effects will also contribute to supersymmetry breaking. However, in models of gauge-mediated supersymmetry breaking, one usually chooses the model parameters in such a way that the virtual exchange of the messengers dominates the effects of the direct gravitational interactions between the hidden and visible sectors. In this scenario, the gravitino mass is typically in the eV to keV range, and is therefore the LSP. The helicity $\pm\frac{1}{2}$ components of $\widetilde{g}_{3/2}$ behave approximately like the goldstino; its coupling to the particles of the MSSM is significantly stronger than a coupling of gravitational strength.

I.3. Parameters of the MSSM: The parameters of the MSSM are conveniently described by considering separately the supersymmetry-conserving sector and the supersymmetry-breaking sector. A careful discussion of the conventions used in defining the MSSM parameters can be found in Ref. 25. For simplicity, consider the case of one generation of quarks, leptons, and their scalar superpartners. The parameters of the supersymmetry-conserving sector consist of: (i) gauge couplings: g_s, g, and g', corresponding to the Standard Model gauge group SU(3)×SU(2)×U(1) respectively; (ii) a supersymmetry-conserving Higgs mass parameter μ; and (iii) Higgs-fermion Yukawa coupling constants: λ_u, λ_d, and λ_e (corresponding to the coupling of one generation of quarks, leptons, and their superpartners to the Higgs bosons and higgsinos).

The supersymmetry-breaking sector contains the following set of parameters: (i) gaugino Majorana masses M_3, M_2 and M_1 associated with the SU(3), SU(2), and U(1) subgroups of the Standard Model; (ii) five scalar squared-mass parameters for the squarks and sleptons, $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, and $M^2_{\widetilde{E}}$ [corresponding to the five electroweak gauge multiplets, *i.e.*, superpartners of $(u,d)_L$, u^c_L, d^c_L, $(\nu, e^-)_L$, and e^c_L,]; (iii) Higgs–squark-squark and Higgs-slepton-slepton trilinear interaction terms, with coefficients A_u, A_d, and A_e (these are the so-called "A-parameters"); and (iv) three scalar Higgs squared-mass parameters—two of which contribute to the diagonal Higgs squared-masses, given by $m_1^2 + |\mu|^2$ and $m_2^2 + |\mu|^2$, and one off-diagonal Higgs squared-mass term, $m_{12}^2 \equiv B\mu$ (which defines the "B-parameter"). These three squared-mass parameters can be re-expressed in terms of the two Higgs vacuum expectation values, v_d and v_u, and one physical Higgs mass. Here, v_d (v_u) is the vacuum expectation value of the Higgs field which couples exclusively to down-type (up-type) quarks and leptons. (Another notation often employed in the literature is $v_1 \equiv v_d$ and $v_2 \equiv v_u$.) Note that $v_d^2 + v_u^2 = (246\ \text{GeV})^2$ is fixed by the W mass (or equivalently by the Fermi constant G_F), while the ratio

$$\tan\beta = v_u/v_d \tag{1}$$

is a free parameter of the model.

The total number of degrees of freedom of the MSSM is quite large, primarily due to the parameters of the soft-supersymmetry-breaking sector. In particular, in the case of three generations of quarks, leptons, and their superpartners, $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, and $M^2_{\widetilde{E}}$ are hermitian 3×3 matrices, and the A-parameters are complex 3×3 matrices. In addition, M_1, M_2, M_3, B and μ are in general complex. Finally, as in the Standard Model, the Higgs-fermion Yukawa couplings, λ_f ($f = u$, d, and e), are complex 3×3 matrices which are related to the quark and lepton mass matrices via: $M_f = \lambda_f v_f/\sqrt{2}$, where $v_e \equiv v_d$ (with v_u and v_d as defined above). However, not all these parameters are physical. Some of the MSSM parameters can be eliminated by expressing interaction eigenstates in terms of the mass eigenstates, with an appropriate redefinition of the MSSM fields to remove unphysical degrees of freedom. The analysis of Ref. 26 shows that the MSSM possesses 124 truly independent parameters. Of these, 18 parameters correspond to Standard Model parameters (including the QCD vacuum angle θ_{QCD}), one corresponds to a Higgs sector parameter (the analogue of the Standard Model Higgs mass), and 105 are genuinely new parameters of the model. The latter include: five real parameters and three CP-violating phases in the gaugino/higgsino sector, 21 squark and slepton masses, 36 new real mixing angles to define the squark and slepton mass eigenstates and 40 new CP-violating phases that can appear in squark and slepton interactions. The most general R-parity-conserving minimal supersymmetric extension of the Standard Model (without additional theoretical assumptions) will be denoted henceforth as MSSM-124 [27].

I.4. The Higgs sector of the MSSM: Before describing the supersymmetric-particle sector, let us consider the Higgs sector of the MSSM [8,9,28]. Despite the large number of potential CP-violating phases among the MSSM-124 parameters, one can show that the tree-level MSSM Higgs sector is automatically CP-conserving. That is, unphysical phases can be absorbed into the definition of the Higgs fields such that $\tan\beta$ is a real parameter (conventionally chosen to be positive). Moreover, the physical neutral Higgs scalars are CP eigenstates. There are five physical Higgs particles in this model: a charged Higgs boson pair ($H^\pm$), two CP-even neutral Higgs bosons (denoted by H_1^0 and H_2^0 where $m_{H_1^0} \le m_{H_2^0}$) and one CP-odd neutral Higgs boson (A^0).

The properties of the Higgs sector are determined by the Higgs potential which is made up of quadratic terms [whose squared-mass coefficients were mentioned above Eq. (1)] and quartic interaction terms. The strengths of the interaction terms are directly related to the gauge couplings by supersymmetry (and are not affected at tree-level by supersymmetry breaking). As a result, $\tan\beta$ [defined in Eq. (1)] and one Higgs mass determine the tree-level Higgs-sector parameters. These include the Higgs masses, an angle α [which measures the component of the original $Y = \pm1$ Higgs doublet states in the physical CP-even neutral scalars], and the Higgs boson couplings.

When one-loop radiative corrections are incorporated, additional parameters of the supersymmetric model enter via virtual loops. The impact of these corrections can be significant [29,30]. For example, at tree-level, MSSM-124 predicts $m_{H_1^0} \le m_Z|\cos 2\beta| \le m_Z$ [8,9]. If this prediction were accurate, it would imply that H_1^0 must be discovered at the LEP-2 collider (running at its maximum energy and luminosity); otherwise MSSM-124 would be ruled out. However, when radiative corrections are included, the light Higgs-mass upper bound may be significantly increased. For example, in Ref. 29, the following approximate upper bound was obtained for $m_{H_1^0}$ (assuming $m_{A^0} > m_Z$) in the limit of $m_Z \ll m_t \ll M_{\widetilde{t}}$ [where top-squark ($\widetilde{t}_L$–$\widetilde{t}_R$) mixing is neglected]

$$m_{H_1^0}^2 \lesssim m_Z^2 + \frac{3g^2 m_Z^4}{16\pi^2 m_W^2}\left\{\left[\frac{2m_t^4 - m_t^2 m_Z^2}{m_Z^4}\right]\ln\left(\frac{M_{\widetilde{t}}^2}{m_t^2}\right) + \frac{m_t^2}{3m_Z^2}\right\}. \tag{2}$$

More refined computations (which include the effects of top-squark mixing, renormalization group improvement, and the leading two-loop contributions) yield $m_{H_1^0} \lesssim 125$ GeV for $m_t = 175$ GeV and a top-squark mass of $M_{\widetilde{t}} \lesssim 1$ TeV [31]. Clearly, the radiative corrections to the Higgs masses can have a significant impact on the search for the Higgs bosons of the MSSM at LEP [32].

I.5. The supersymmetric-particle sector: Consider the sector of supersymmetric particles (*sparticles*) in the MSSM. The supersymmetric partners of the gauge and Higgs bosons are fermions, whose names are obtained by appending "ino" at the end of the corresponding Standard Model particle name. The *gluino* is the color octet Majorana fermion partner of the gluon with mass $M_{\widetilde{g}} = |M_3|$. The supersymmetric partners of the electroweak gauge and Higgs bosons (the *gauginos* and *higgsinos*) can mix. As a result, the physical mass eigenstates are model-dependent linear combinations of these states, called *charginos* and *neutralinos*, which are obtained by diagonalizing the corresponding mass matrices. The chargino-mass matrix depends on M_2, μ, $\tan\beta$ and m_W [33].

The corresponding chargino-mass eigenstates are denoted by $\widetilde{\chi}_1^+$ and $\widetilde{\chi}_2^+$, with masses

$$\begin{aligned} M^2_{\widetilde{\chi}_1^+,\widetilde{\chi}_2^+} = \tfrac{1}{2}\Big\{ & |\mu|^2 + |M_2|^2 + 2m_W^2 \\ & \mp \Big[\left(|\mu|^2 + |M_2|^2 + 2m_W^2\right)^2 - 4|\mu|^2|M_2|^2 \\ & \qquad - 4m_W^4 \sin^2 2\beta + 8m_W^2 \sin 2\beta\,\mathrm{Re}(\mu M_2)\Big]^{1/2}\Big\}, \end{aligned} \tag{3}$$

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \leq M_{\widetilde{\chi}_2^+}$. If *CP*-violating effects are ignored (in which case, M_2 and μ are real parameters), then one can choose a convention where $\tan\beta$ and M_2 are positive. (Note that the relative sign of M_2 and μ is meaningful. The sign of μ is convention-dependent; the reader is warned that both sign conventions appear in the literature.) The sign convention for μ implicit in Eq. (3) is used by the LEP collaborations [12] in their plots of exclusion contours in the M_2 *vs.* μ plane derived from the non-observation of $e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$.

The neutralino mass matrix depends on M_1, M_2, μ, $\tan\beta$, m_Z, and the weak mixing angle θ_W [33]. The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ ($i = 1, \ldots 4$), according to the convention that $M_{\widetilde{\chi}_1^0} \leq M_{\widetilde{\chi}_2^0} \leq M_{\widetilde{\chi}_3^0} \leq M_{\widetilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or Higgsino state, it may be convenient to use the corresponding nomenclature. For example, if M_1 and M_2 are small compared to m_Z (and $|\mu|$), then the lightest neutralino $\widetilde{\chi}_1^0$ will be nearly a pure photino, $\widetilde{\gamma}$ (the supersymmetric partner of the photon).

The supersymmetric partners of the quarks and leptons are spin-zero bosons: the *squarks*, charged *sleptons*, and *sneutrinos*. For simplicity, only the one-generation case is illustrated below (using first-generation notation). For a given fermion f, there are two supersymmetric partners $\widetilde{f}_L$ and $\widetilde{f}_R$ which are scalar partners of the corresponding left and right-handed fermion. (There is no $\widetilde{\nu}_R$ in the MSSM.) However, in general, $\widetilde{f}_L$ and $\widetilde{f}_R$ are not mass-eigenstates since there is $\widetilde{f}_L$-$\widetilde{f}_R$ mixing which is proportional in strength to the corresponding element of the scalar squared-mass matrix [34]

$$M_{LR}^2 = \begin{cases} m_d(A_d - \mu\tan\beta), & \text{for "down"-type } f \\ m_u(A_u - \mu\cot\beta), & \text{for "up"-type } f, \end{cases} \tag{4}$$

where m_d (m_u) is the mass of the appropriate "down" ("up") type quark or lepton. The signs of the A-parameters are also convention-dependent; see Ref. 25. Due to the appearance of the *fermion* mass in Eq. (4), one expects M_{LR} to be small compared to the diagonal squark and slepton masses, with the possible exception of the top-squark, since m_t is large, and the bottom-squark and tau-slepton if $\tan\beta \gg 1$.

The (diagonal) L- and R-type squark and slepton squared-masses are given by [2]

$$\begin{aligned} M^2_{\widetilde{f}_L} &= M^2_{\widetilde{F}} + m_f^2 + (T_{3f} - e_f \sin^2\theta_W) m_Z^2 \cos 2\beta\,, \\ M^2_{\widetilde{f}_R} &= M^2_{\widetilde{R}} + m_f^2 + e_f \sin^2\theta_W m_Z^2 \cos 2\beta\,, \end{aligned} \tag{5}$$

where $M^2_{\widetilde{F}} = M^2_{\widetilde{Q}}$ $[M^2_{\widetilde{L}}]$ for $\widetilde{u}_L$ and $\widetilde{d}_L$ $[\widetilde{\nu}_L$ and $\widetilde{e}_L]$, and $M^2_{\widetilde{R}} = M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$ and $M^2_{\widetilde{E}}$ for $\widetilde{u}_R$, $\widetilde{d}_R$, and $\widetilde{e}_R$, respectively. In addition, $e_f = \frac{2}{3}, -\frac{1}{3}, 0, -1$ for $f = u, d, \nu$, and e, respectively, $T_{3f} = \frac{1}{2}$ $[-\frac{1}{2}]$ for up-type [down-type] squarks and sleptons, and m_f is the corresponding quark or lepton mass. Squark and slepton mass eigenstates, generically called $\widetilde{f}_1$ and $\widetilde{f}_2$ (these are linear combinations of $\widetilde{f}_L$ and $\widetilde{f}_R$) are obtained by diagonalizing the corresponding 2×2 squared-mass matrices.

In the case of three generations, the general analysis is more complicated. The scalar squared-masses [$M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ in Eq. (5)], the fermion masses m_f and the A-parameters are now 3×3 matrices as noted in Section I.3. Thus, to obtain the squark and slepton mass eigenstates, one must diagonalize 6×6 mass matrices. As a result, intergenerational mixing is possible, although there are some constraints from the nonobservation of FCNC's [14]. In practice, because off-diagonal scalar mixing is appreciable only for the third generation, this additional complication can usually be neglected.

It should be noted that all mass formulae quoted in this section are tree-level results. One-loop corrections will modify all these results, and eventually must be included in any precision study of supersymmetric phenomenology.

I.6. Reducing the MSSM parameter freedom: Even in the absence of a fundamental theory of supersymmetry breaking, one is hard-pressed to regard MSSM-124 as a fundamental theory. For example, no fundamental explanation is provided for the origin of electroweak symmetry breaking. Moreover, MSSM-124 is not a phenomenologically viable theory over most of its parameter space. Among the phenomenologically deficiencies are: (i) no conservation of the separate lepton numbers L_e, L_μ, and L_τ; (ii) unsuppressed FCNC's; and (iii) new sources of CP-violation that are inconsistent with the experimental bounds. As a result, almost the entire MSSM-124 parameter space is ruled out! This theory is viable only at very special "exceptional" points of the full parameter space.

MSSM-124 is also theoretically deficient since it provides no explanation for the origin of the supersymmetry-breaking parameters (and in particular, why these parameters should conform to the exceptional points of the parameter space mentioned above). Moreover, the MSSM contains many new sources of CP violation. For example, some combination of the complex phases of the gaugino-mass parameters, the A-parameters, and μ must be less than of order 10^{-2}–10^{-3} (for a supersymmetry-breaking scale of 100 GeV) to avoid generating electric dipole moments for the neutron, electron, and atoms in conflict with observed data [35].

There are two general approaches for reducing the parameter freedom of MSSM-124. In the low-energy approach, an attempt is made to elucidate the nature of the exceptional points in the MSSM-124 parameter space that are phenomenologically viable. Consider the following two possible choices. First, one can assume that $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, $M^2_{\widetilde{E}}$ and the matrix A-parameters are generation-independent (horizontal universality [5,26,36]). Alternatively, one can simply require that all the aforementioned matrices are flavor diagonal in a basis where the quark and lepton mass matrices are diagonal (flavor alignment [37]). In either case, L_e, L_μ, and L_τ are separately conserved, while tree-level FCNC's are automatically absent. In both cases, the number of free parameters characterizing the MSSM is substantially less than 124. Both scenarios are phenomenologically viable, although there is no strong theoretical basis for either scenario.

In the high-energy approach, one treats the parameters of the MSSM as running parameters and imposes a particular structure on the soft-supersymmetry-breaking terms at a common high-energy scale [such as the Planck scale ($M_{\rm P}$)]. Using the renormalization group equations, one can then derive the low-energy MSSM parameters. The initial conditions (at the appropriate high-energy scale) for the renormalization group equations depend on the mechanism by which supersymmetry breaking is communicated to the effective low energy theory. Examples of this scenario are provided by models of gravity-mediated and gauge-mediated supersymmetry breaking (see Section I.2). One bonus of such an approach is that one of the diagonal Higgs squared-mass parameters is typically driven negative by renormalization group evolution. Thus, electroweak symmetry breaking is generated radiatively, and the resulting electroweak symmetry-breaking scale is intimately tied to the scale of low-energy supersymmetry breaking.

One of the most common predictions of the high-energy approach is the unification of gaugino mass parameters at some high-energy scale $M_{\rm X}$, *i.e.*,

$$M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}\,. \qquad (6)$$

This is a common prediction of both grand unified supergravity models and gauge-mediated supersymmetry-breaking models. Consequently, the effective low-energy gaugino mass parameters (at the electroweak scale) are related:

$$M_3 = (g_s^2/g^2)M_2\,, \qquad M_1 = (5g'^2/3g^2)M_2 \simeq 0.5M_2\,. \qquad (7)$$

In this case, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$. However, the assumption of gaugino-mass unification could prove false and must eventually be tested experimentally. For example, the phenomenology of neutralinos in a model with $M_1 \simeq M_2$ can differ in some interesting ways from the standard phenomenology based on Eq. (7), as shown in Ref. 38.

I.7. The constrained MSSMs: mSUGRA, GMSB, and SGUTs: One way to guarantee the absence of significant FCNC's mediated by virtual supersymmetric-particle exchange is to posit that the diagonal soft-supersymmetry-breaking scalar squared-masses are universal at some energy scale. In models of gauge-mediated supersymmetry breaking, scalar squared-masses are expected to be flavor independent since gauge forces are flavor-blind. In the *minimal* supergravity (mSUGRA) framework [1,2], the soft-supersymmetry breaking parameters at the Planck scale take a particularly simple form in which the scalar squared-masses and the A-parameters are flavor diagonal and universal [20]:

$$\begin{aligned}
&M^2_{\widetilde{Q}}(M_{\rm P}) = M^2_{\widetilde{U}}(M_{\rm P}) = M^2_{\widetilde{D}}(M_{\rm P}) = m_0^2\mathbf{1}\,,\\
&M^2_{\widetilde{L}}(M_{\rm P}) = M^2_{\widetilde{E}}(M_{\rm P}) = m_0^2\mathbf{1}\,,\\
&m_1^2(M_{\rm P}) = m_2^2(M_{\rm P}) = m_0^2\,,\\
&A_U(M_{\rm P}) = A_D(M_{\rm P}) = A_L(M_{\rm P}) = A_0\mathbf{1}\,,
\end{aligned} \qquad (8)$$

where $\mathbf{1}$ is a 3×3 identity matrix in generation space. Renormalization group evolution is then used to derive the values of the supersymmetric parameters at the low-energy (electroweak) scale. For example, to compute squark and slepton masses, one must use the *low-energy* values for $M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ in Eq. (5). Through the renormalization group running with boundary conditions specified in Eq. (7) and Eq. (8), one can show that the low-energy values of $M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ depend primarily on m_0^2 and $m^2_{1/2}$. A number of useful approximate analytic expressions for superpartner masses in terms of the mSUGRA parameters can be found in Ref. 39.

Clearly, in the mSUGRA approach, the MSSM-124 parameter freedom has been sharply reduced. For example, typical mSUGRA models give low-energy values for the scalar mass parameters that satisfy $M_{\widetilde{L}} \approx M_{\widetilde{E}} < M_{\widetilde{Q}} \approx M_{\widetilde{U}} \approx M_{\widetilde{D}}$ with the squark mass parameters somewhere between a factor of 1–3 larger than the slepton mass parameters (*e.g.*, see Ref. 39). More precisely, the low-energy values of the squark mass parameters of the first two generations are roughly degenerate, while $M_{\widetilde{Q}_3}$ and $M_{\widetilde{U}_3}$ are typically reduced by a factor of 1–3 from the values of the first and second generation squark mass parameters because of renormalization effects due to the heavy top quark mass.

As a result, one typically finds that four flavors of squarks (with two squark eigenstates per flavor) and $\widetilde{b}_R$ are nearly mass-degenerate. The $\widetilde{b}_L$ mass and the diagonal $\widetilde{t}_L$ and $\widetilde{t}_R$ masses are reduced compared to the common squark mass of the first two generations. (If $\tan\beta \gg 1$, then the pattern of third generation squark masses is somewhat altered; *e.g.*, see Ref. 40.) In addition, there are six flavors of nearly mass-degenerate sleptons (with two slepton eigenstates per flavor for the charged sleptons and one per flavor for the sneutrinos); the sleptons are expected to be somewhat lighter than the mass-degenerate squarks. Finally, third generation squark masses and tau-slepton masses are sensitive to the strength of the respective $\widetilde{f}_L$–$\widetilde{f}_R$ mixing as discussed below Eq. (4).

Due to the implicit $m_{1/2}$ dependence in the low-energy values of $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$ and $M^2_{\widetilde{D}}$, there is a tendency for the gluino in mSUGRA models to be lighter than the first and second generation squarks. Moreover, the LSP is typically the lightest neutralino, $\widetilde{\chi}^0_1$, which tends to be dominated by its gaugino components. However, there are some regions of mSUGRA parameter space where the above conclusions do not hold. For example, one can reject those mSUGRA parameter regimes in which the LSP is a chargino.

One can count the number of independent parameters in the mSUGRA framework. In addition to 18 Standard Model parameters (excluding the Higgs mass), one must specify m_0, $m_{1/2}$, A_0, and Planck-scale values for μ and B-parameters (denoted by μ_0 and B_0). In principle, A_0, B_0 and μ_0 can be complex, although in the mSUGRA approach, these parameters are taken (arbitrarily) to be real. As previously noted, renormalization group evolution is used to compute the low-energy values of the mSUGRA parameters, which then fixes all the parameters of the low-energy MSSM. In particular, the two Higgs vacuum expectation values (or equivalently, m_Z and $\tan\beta$) can be expressed as a function of the Planck-scale supergravity parameters. The simplest procedure is to remove μ_0 and B_0 in favor of m_Z and $\tan\beta$ (the sign of μ_0 is not fixed in this process). In this case, the MSSM spectrum and its interaction strengths are determined by five parameters: m_0, A_0, $m_{1/2}$, $\tan\beta$, and the sign of μ_0, in addition to the 18 parameters of the Standard Model. However, the mSUGRA approach is probably too simplistic. Theoretical considerations suggest that the universality of Planck-scale soft-supersymmetry-breaking parameters is not generic [41].

In the minimal gauge-mediated supersymmetry-breaking (GMSB) approach, there is one effective mass scale, Λ, that determines all low-energy scalar and gaugino mass parameters through loop-effects (while the resulting A-parameters are suppressed). In order that the resulting superpartner masses be of order 1 TeV or less, one must have $\Lambda \sim 100$ TeV. The origin of the μ and B-parameters is quite model dependent and lies somewhat outside the ansatz of gauge-mediated supersymmetry breaking. The simplest models of this type are even more restrictive than mSUGRA, with two fewer degrees of freedom. However, minimal GMSB is not a fully realized model. The sector of supersymmetry-breaking dynamics can be very complex, and it is fair to say that no complete model of gauge-mediated supersymmetry yet exists that is both simple and compelling.

It was noted in Section I.2 that the gravitino is the LSP in GMSB models. Thus, in such models, the next-to-lightest supersymmetric particle (NLSP) plays a crucial role in the phenomenology of supersymmetric particle production and decay. Note that unlike the LSP, the NLSP can be charged. In GMSB models, the most likely candidates for the NLSP are $\widetilde{\chi}^0_1$ and $\widetilde{\tau}^{\pm}_R$. The NLSP will decay into its superpartner plus a gravitino (*e.g.*, $\widetilde{\chi}^0_1 \to \gamma\widetilde{g}_{3/2}$, $\widetilde{\chi}^0_1 \to Z\widetilde{g}_{3/2}$ or $\widetilde{\tau}^{\pm}_R \to \tau^{\pm}\widetilde{g}_{3/2}$), with lifetimes and branching ratios that depend on the model parameters.

Different choices for the identity of the NLSP and its decay rate lead to a variety of distinctive supersymmetric phenomenologies [42]. For example, a long-lived $\widetilde{\chi}^0_1$-NLSP that decays outside collider detectors leads to supersymmetric decay chains with missing energy in association with leptons and/or hadronic jets (this case is indistinguishable from the canonical phenomenology of the $\widetilde{\chi}^0_1$-LSP). On the other hand, if $\widetilde{\chi}^0_1 \to \gamma\widetilde{g}_{3/2}$ is the dominant decay mode, and the decay occurs inside the detector, then nearly *all* supersymmetric particle decay chains would contain a photon. In contrast, the case of a $\widetilde{\tau}^{\pm}_R$-NLSP would lead either to a new long-lived charged particle (*i.e.*, the $\widetilde{\tau}^{\pm}_R$) or to supersymmetric particle decay chains with τ-leptons.

Finally, grand unification can impose additional constraints on the MSSM parameters. Perhaps one of the most compelling hints for low-energy supersymmetry is the unification of SU(3)×SU(2)×U(1) gauge couplings predicted by models of supersymmetric grand unified theories (SGUTs) [5,43] (with the supersymmetry-breaking scale of order 1 TeV or below). Gauge coupling unification, which takes place at an energy scale of order 10^{16} GeV, is quite robust (*i.e.*, the unification depends weakly on the details of the theory at the unification scale). Current low-energy data is in fair agreement with the predictions of supersymmetric grand unification as discussed in Section I.8.

Additional SGUT predictions arise through the unification of the Higgs-fermion Yukawa couplings (λ_f). There is some evidence that $\lambda_b = \lambda_\tau$ leads to good low-energy phenomenology [44], and an intriguing possibility that $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [45,40] in the parameter regime where $\tan\beta \simeq m_t/m_b$. Finally, grand unification imposes constraints on the soft-supersymmetry-breaking parameters. For example, gaugino-mass unification leads to the relations given in Eq. (7). Diagonal squark and slepton soft-supersymmetry-breaking scalar masses may also be unified, which is analogous to the unification of Higgs-fermion Yukawa couplings.

In the absence of a fundamental theory of supersymmetry breaking, further progress will require a detailed knowledge of the supersymmetric-particle spectrum in order to determine the nature of the high-energy parameters. Of course, any of the theoretical assumptions described in this section could be wrong and must eventually be tested experimentally.

I.8. The MSSM and precision of electroweak data: The MSSM provides a framework that can be tested by precision electroweak data. The level of accuracy of the measured Z decay observables at LEP and SLC is sufficient to test the structure of the one-loop radiative corrections of the electroweak model [46]. Thus the precision electroweak data is potentially sensitive to the virtual effects of undiscovered particles. Combining the most recent LEP and SLC electroweak results (including the limits obtained from the direct Higgs search at LEP) with the recent top-quark mass measurement at the Tevatron, a preference is found [47,48] for a light Higgs boson mass of order m_Z, which is consistent with the MSSM Higgs mass upper bound discussed in Section I.4. [More precisely, in Ref. 48, the best fit value for the mass of the Standard Model Higgs boson ranges from about 83 to 140 GeV, while the 95% CL upper limit ranges from 287 to 361 GeV, depending on the value used for $\alpha(m_Z)$. (Similar results have been obtained in Ref. 47). Moreover, for Z decay observables, the effects of virtual supersymmetric-particle exchange are suppressed by a factor of $m_Z^2/M_{\rm SUSY}^2$, and therefore decouple in the limit of large supersymmetric-particle masses. It follows that for $M_{\rm SUSY} \gg m_Z$ (in practice, it is sufficient to have all supersymmetric-particle masses above 200 GeV), the MSSM yields an equally good fit to the precision electroweak data as compared to the Standard Model fit.

At present, a global fit of the electroweak data by Erler and Langacker (EL) [48] is in excellent agreement with the predictions of the Standard Model. If some supersymmetric particles are light (say, below 200 GeV but above present experimental bounds deduced from direct searches), then it is possible that the EL fit could be modified in the MSSM. A few years ago, when the rate for $Z \to b\bar{b}$ was four standard deviations above the Standard Model prediction, the possibility that the MSSM could improve the global electroweak fit was taken quite seriously. However, it is hard to imagine that the MSSM could significantly improve the quality of the current EL fit (given that the Standard Model fit is already quite good, and a global fit in the context of the MSSM would necessarily involve more degrees of freedom). On the other hand, the MSSM could significantly decrease the goodness of the Standard Model fit. This possibility has been explored recently in Ref. 49. Their analysis shows that one can slightly reduce the allowed region of mSUGRA and GMSB model parameter spaces beyond the region already ruled out by the non-observation of direct supersymmetric particle production.

Electroweak observables are also sensitive to the strong coupling constant through the QCD radiative corrections. The EL global fit extracts a value of $\alpha_s(m_Z) = 0.1214 \pm 0.0031$, which is in good agreement with the world average of $\alpha_s(m_Z) = 0.1191 \pm 0.0018$ [48]. This result has important implications for the viability of supersymmetric unification. Given the low-energy values of the electroweak couplings $g(m_Z)$ and $g'(m_Z)$, one can predict $\alpha_s(m_Z)$ by using the MSSM renormalization group equations to extrapolate to higher energies and imposing the unification condition on the three gauge couplings at some high-energy scale, $M_{\rm X}$. This procedure (which fixes $M_{\rm X}$) can be successful (*i.e.*, three running couplings will meet at a single point) only for a unique value of $\alpha_s(m_Z)$. The extrapolation depends somewhat on the low-energy supersymmetric spectrum (so-called low-energy "threshold effects") and on the SGUT spectrum (high-energy threshold effects), which can somewhat alter the evolution of couplings. For example, allowing for low-energy threshold effects but neglecting threshold corrections near the unification scale, Ref. 50 finds that SGUT unification in the mSUGRA model predicts that $\alpha_s(m_Z) > 0.126$, which is only in slight disagreement with the results of the EL fit. (Similar results have been obtained in Ref. 51.) Taking SGUT threshold effects into account could either slightly increase or decrease the predicted value of $\alpha_s(m_Z)$, depending on the details of the model. In contrast, the corresponding result for the Standard Model extrapolation, $\alpha_s(m_Z) \simeq 0.073 \pm 0.002$ [52], is many standard deviations away from the experimentally observed result.

I.9. Beyond the MSSM: Non-minimal models of low-energy supersymmetry can also be constructed. One approach is to add new structure beyond the Standard Model at the TeV scale or below. The supersymmetric extension of such a theory would be a non-minimal extension of the MSSM. Possible new structures include: (i) the supersymmetric generalization of the see-saw model of neutrino masses [53,54]; (ii) an enlarged electroweak gauge group beyond SU(2)×U(1) [55]; (iii) the addition of new, possibly exotic, matter multiplets [*e.g.*, a vector-like color triplet with electric charge $\frac{1}{3}e$; such states sometimes occur as low-energy remnants in $\rm E_6$ grand unification models]; and/or (iv) the addition of low-energy SU(3)×SU(2)×U(1) singlets [56]. A possible theoretical motivation for such new structure arises from the study of phenomenologically viable string theory ground states [57].

A second approach is to retain the minimal particle content of the MSSM but remove the assumption of R-parity invariance. The most general R-parity-violating (RPV) theory involving the MSSM spectrum introduces many new parameters to both the supersymmetry-conserving and the supersymmetry-breaking sectors. Each new interaction term violates either B or L conservation. For example, consider new scalar-fermion Yukawa couplings derived from the following interactions:

$$(\lambda_L)_{pmn}\widehat{L}_p\widehat{L}_m\widehat{E}^c_n + (\lambda'_L)_{pmn}\widehat{L}_p\widehat{Q}_m\widehat{D}^c_n + (\lambda_B)_{pmn}\widehat{U}^c_p\widehat{D}^c_m\widehat{D}^c_n\,, \quad (9)$$

where p, m, and n are generation indices, and gauge group indices are suppressed. In the notation above, $\widehat{Q}$, $\widehat{U}^c$, $\widehat{D}^c$, $\widehat{L}$, and $\widehat{E}^c$ respectively represent $(u,d)_L$, u^c_L, d^c_L, $(\nu,\, e^-)_L$, and e^c_L and the corresponding superpartners. The Yukawa interactions are obtained from Eq. (9) by taking all possible combinations involving two fermions and one scalar superpartner. Note that the term in Eq. (9) proportional to λ_B violates B, while the other two terms violate L.

Phenomenological constraints on various low-energy B- and L-violating processes yield limits on each of the coefficients $(\lambda_L)_{pmn}$, $(\lambda'_L)_{pmn}$ and $(\lambda_B)_{pmn}$ taken one at a time [58]. If more than one coefficient is simultaneously non-zero, then the limits are in general more complicated. All possible RPV terms cannot be simultaneously present and unsuppressed; otherwise the proton decay rate would be many orders of magnitude larger than the present experimental bound. One way to avoid proton decay is to impose B- or L-invariance (either one alone would suffice). Otherwise, one must accept the requirement that certain RPV coefficients must be extremely suppressed.

If R-parity is not conserved, supersymmetric phenomenology exhibits features that are quite distinct from that of the MSSM. The LSP is no longer stable, which implies that not all supersymmetric decay chains must yield missing-energy events at colliders. Both $\Delta L = 1$ and $\Delta L = 2$ phenomena are allowed (if L is violated), leading to neutrino masses and mixing [59], neutrinoless double beta decay [60], sneutrino-antisneutrino mixing [54,61], and s-channel resonant production of the sneutrino in e^+e^- collisions [62]. Since the distinction between the Higgs and matter multiplets is lost, R-parity violation permits the mixing of sleptons and Higgs bosons, the mixing of neutrinos and neutralinos, and the mixing of charged leptons and charginos, leading to more complicated mass matrices and mass eigenstates than in the MSSM.

Squarks can be regarded as leptoquarks since if $\lambda'_L \neq 0$, the following processes are allowed: $e^+\overline{u}_m \to \overline{\widetilde{d}}_n \to e^+\overline{u}_m,\, \overline{\nu}\overline{d}_m$ and $e^+d_m \to \widetilde{u}_n \to e^+d_m$. (As above, m and n are generation labels, so that $d_2 = s$, $d_3 = b$, *etc.*) These processes have received much attention during the past year as a possible explanation for the HERA high Q^2 anomaly [63].

The theory and phenomenology of alternative low-energy supersymmetric models (such as models with R-parity violation) and its consequences for collider physics have only recently begun to attract significant attention. Experimental and theoretical constraints place some restrictions on these approaches, although no comprehensive treatment has yet appeared in the literature.

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SUPERSYMMETRY, PART II (EXPERIMENT)

(by M. Schmitt)

II.1. Introduction: The theoretical strong points of supersymmetry (SUSY) have motivated many searches for supersymmetric particles. Most of these have been guided by the MSSM and are based on the canonical missing-energy signature caused by the escape of the LSP's ('lightest supersymmetric particles'). More recently, other scenarios have received considerable attention from experimenters, widening the range of topologies in which new physics might be found.

Unfortunately, no convincing evidence for the production of supersymmetric particles has been found. The most far reaching laboratory searches have been performed at the Tevatron and at LEP, and these are the main topic of this review. In addition, there are a few special opportunities exploited by HERA and certain fixed-target experiments.

In order to keep this review as current as possible, the most recent results have been used, including selected preliminary results reported at the High Energy Conference of the European Physical Society, held in Jerusalem during August 1997.

Theoretical aspects of supersymmetry have been covered in Part I of this review by H.E. Haber (see also Ref. 1, 2); we use his notations and terminology.

II.2. Common supersymmetry scenarios: In the 'canonical' scenario [1], supersymmetric particles are pair-produced and decay directly or via cascades to the LSP. For most typical choices of model parameters, the lightest neutralino is the LSP. Conservation of R-parity is assumed, so the LSP's do not decay and escape detection, causing an apparent transverse momentum imbalance, $p_T^{\rm miss}$ (also referred to as missing transverse energy, $\not{E}_T$), and missing energy, $E^{\rm miss}$. There are always two LSP's per event. The searches demand significant $p_T^{\rm miss}$ as the main discriminant against Standard Model (SM) processes; collimated jets, isolated leptons or photons, and appropriate kinematic cuts provide additional handles to reduce backgrounds.

The conservation of R-parity is not required in supersymmetry, however, and in some searches it is assumed that supersymmetric particles decay via interactions which violate R-parity (RPV), and hence, lepton and/or baryon number. For the most part the production of superpartners is unchanged, but in general the missing-energy signature is lost. Depending on the choice of the R-parity–breaking interaction, SUSY events are characterized by excess leptons or hadronic jets, and in many cases it is relatively easy to suppress SM backgrounds [3]. In this scenario the pair-production of LSP's, which need not be $\widetilde{\chi}_1^0$'s or $\widetilde{\nu}$'s, is a significant SUSY signal.

In models assuming gauge-mediated supersymmetry breaking (GMSB) [4], the gravitino $\widetilde{g}_{3/2}$ is a weakly-interacting fermion with a mass so small that it can be neglected when considering the event kinematics. It is the LSP, and the lightest neutralino decays to it radiatively, possibly with a very long lifetime. For the most part the decays and production of other superpartners are the same as in the canonical scenario, so when the $\widetilde{\chi}_1^0$ lifetime is not too long, the event topologies are augmented by the presence of photons which can be energetic and isolated. If the $\widetilde{\chi}_1^0$ lifetime is so long that it decays outside of the detector, the event topologies are the same as in the canonical scenario. In some variants of this theory the right-sleptons are lighter than the lightest neutralino, and they decay to a lepton and a gravitino. This decay might occur after the slepton exits the apparatus, depending on model parameters.

Finally, in another scenario the gluino $\widetilde{g}$ is assumed to be very light ($M_{\widetilde{g}} < 5$ GeV/c^2) [5]. It is a color-octet fermion which can saturate the decays of charginos and neutralinos. In this scenario the decay of the gluino to the lightest neutralino is kinematically suppressed, so long-lived supersymmetric hadrons ($\widetilde{g} + g$ bound states called R^0's) are formed [6]. These will produce hadronic showers in the calorimeters, thus spoiling the canonical missing-energy signature on which most SUSY searches rely. The exclusion of a light gluino is not settled (see the Listings), however, given recent experimental and theoretical developments, this issue may well be settled in the near future.

II.3. Experimental issues: Before describing the results of the searches, a few words about the issues facing the experimenters are in order.

Given no signal for supersymmetric particles, experimenters are forced to derive limits on their production. The most general formulation of supersymmetry is so flexible that few universal bounds can be obtained. Often more restricted forms of the theory are evoked for which predictions are more definite—and exclusions more constraining. The most popular of these is minimal supergravity ('mSUGRA'). As explained in the Part I of this review, parameter freedom is drastically reduced by requiring related parameters to be equal at the unification scale. Thus, the gaugino masses are equal with value $m_{1/2}$, and the slepton, squark, and Higgs masses depend on a *common* scalar mass parameter, m_0. In the individual experimental analyses, only some of these assumptions are necessary. For example, the gluon and squark searches at proton machines constrain mainly M_3 and a scalar mass parameter m_0 for the squark masses, while the chargino, neutralino, and slepton searches at e^+e^- colliders constrain M_2 and a scalar mass parameter m_0 for the slepton masses. In addition, results from the Higgs searches can be used to constrain $m_{1/2}$ and m_0 as a function of $\tan\beta$. (The full analysis involves large radiative corrections coming from squark mixing, which is where the dependence on $m_{1/2}$ and m_0 enter.) In the mSUGRA framework, all the scalar mass parameters m_0 are the same and the three gaugino mass parameters are proportional to $m_{1/2}$, so limits from squarks, sleptons, charginos, gluinos, and Higgs all can be used to constrain the parameter space.

While the mSUGRA framework is convenient, it is based on several theoretical assumptions which are highly specific, so limits presented in this framework cannot easily be applied to other supersymmetric models. Serious attempts to reduce the model dependence of experimental exclusions have been made recently. When model-independent results are impossible, the underlying assumptions and their consequences are carefully delineated. This is easier to achieve at e^+e^- colliders than at proton machines.

The least model-dependent result from any experiment is the upper limit on the cross section. It requires only the number N of candidate events, the integrated luminosity $\mathcal{L}$, the expected backgrounds b, and the acceptance ϵ for a given signal. The upper limit on the number of signal events for a given confidence level $N^{\rm upper}$ is computed from N and b (see review of Statistics). The experimental bound is simply

$$\epsilon \cdot \sigma < N^{\rm upper}/\mathcal{L}. \quad (1)$$

This information is nearly always reported, but some care is needed to understand how the acceptance was estimated, since it is often sensitive to assumptions about masses and branching ratios. Also, in the more complicated analyses, $N^{\rm upper}$ also changes as a result of the optimization for a variety of possible signals.

The theoretical parameter space is constrained by computing $\epsilon \cdot \sigma$ of Eq. (1) in terms of the relevant parameters while $N^{\rm upper}/\mathcal{L}$ is fixed by experiment. Even after the theoretical scenario and assumptions have been specified, some choice remains about how to present the constraints. The quantity $\epsilon \cdot \sigma$ may depend on three or more parameters, yet in a printed page one usually can display limits only in a two-dimensional space. Three rather different tactics are employed by experimenters:

- Select "typical" values for the parameters not shown. These may be suggested by theory, or values giving more conservative—or more powerful—results may be selected. Although the values are usually specified, one sometimes has to work to understand the possible 'loopholes.'
- Scan the parameters not shown. The lowest value for $\epsilon \cdot \sigma$ is used in Eq. (1), thereby giving the weakest limit for the parameters shown. As a consequence, the limit applies for all values of the parameters *not* shown.
- Scan parameters to find the lowest acceptance ϵ and use it as a constant in Eq. (1). The limits are then safe from theoretical uncertainties but may be over-conservative, hiding powerful constraints existing in more typical cases.

Judgement is exercised: the second option is the most correct but may be impractical or uninteresting; most often representative cases are presented. These latter become standard, allowing a direct comparison of experiments, and also the opportunity to combine results.

Limits reported here are derived for 95% C.L. unless noted otherwise.

II.4. Supersymmetry searches in e^+e^- colliders: The center-of-mass energy of the large electron-positron collider (LEP) at CERN has been raised well above the Z peak in recent years. After collecting approximately 150 pb^{-1} at LEP 1, each experiment (ALEPH, DELPHI, L3, OPAL) has accumulated the first data at LEP 2: about 5.7 pb^{-1} at $\sqrt{s} \sim 133$ GeV (1995) [7], 10 pb^{-1} at 161 GeV and 11 pb^{-1} at 172 GeV (1996). This review emphasizes the most recent LEP 2 results.

At LEP experiments and SLD at SLAC excluded all visible supersymmetric particles up to about half the Z mass (see the Listings for details). These limits come mainly from the comparison of the measured Z widths to the SM expectations, and depend less on the details of the SUSY particle decays than do the results of direct searches [8]. The new data taken at higher energies allow much stronger limits to be set, although the complex interplay of masses, cross sections, and branching ratios makes simple general limits impossible to specify.

The main signals come from SUSY particles with charge, weak isospin, or large Yukawa couplings. The gauge fermions (charginos and neutralinos) generally are produced with large cross sections, while the scalar particles (sleptons and squarks) are suppressed near threshold by kinematic factors.

Charginos are produced via γ^*, Z^*, and $\tilde{\nu}_e$ exchange. Cross sections are in the 1–10 pb range, but can be an order of magnitude smaller when $M_{\tilde{\nu}_e}$ is less than 100 GeV/c^2 due to the destructive interference between s- and t-channel amplitudes. Under the same circumstances, neutralino production is enhanced, as the t-channel $\tilde{e}$ exchange completely dominates the s-channel Z^* exchange. When Higgsino components dominate the field content of charginos and neutralinos, cross sections are large and insensitive to slepton masses.

Sleptons and squarks are produced via γ^* and Z^* exchange; for selectrons there is an important additional contribution from t-channel neutralino exchange which generally increases the cross section substantially. Although the Tevatron experiments have placed general limits on squark masses far beyond the reach of LEP, a light top squark (stop) could still be found since the flavor eigenstates can mix to give a large splitting between the mass eigenstates. The coupling of the lightest stop to the Z^* will vary with the mixing angle, however, and for certain values, even vanish, so the limits on squarks from LEP depend on the mixing angle assumed.

The various SUSY particles considered at LEP usually decay directly to SM particles and LSP's, so signatures commonly consist of some combination of jets, leptons, possibly photons, and missing energy. Consequently the search criteria are geared toward a few distinct topologies. Although they may be optimized for one specific signal, they are often efficient for others. For example, acoplanar jets are expected in both $\tilde{t}_1\bar{\tilde{t}}_1$ and $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production, and acoplanar leptons for both $\tilde{\ell}^+\tilde{\ell}^-$ and $\tilde{\chi}^+\tilde{\chi}^-$.

The major backgrounds come from three sources. First, there are the so-called 'two-photon interactions,' in which the beam electrons emit photons which combine to produce a low mass hadronic or leptonic system leaving little visible energy in the detector. Since the electrons are seldom deflected through large angles, $p_T^{\rm miss}$ is low. Second, there is difermion production, usually accompanied by a large initial-state radiation induced by the Z pole, which gives events that are well balanced with respect to the beam direction. Finally, there is four-fermion production through states with one or two resonating bosons (W^+W^-, ZZ, $We\nu$, Ze^+e^-, etc.) which can give events with large $E^{\rm miss}$ and $p_T^{\rm miss}$ due to neutrinos and electrons lost down the beam pipe.

In the canonical case, $E^{\rm miss}$ and $p_T^{\rm miss}$ are large enough to eliminate most of these backgrounds. The e^+e^- initial state is well defined so searches utilize both transverse and longitudinal momentum components. It is possible to measure the missing mass ($M_{\rm miss} = \{(\sqrt{s} - E_{\rm vis})^2 - \vec{p}^{\,2}_{\rm vis}\}^{1/2}$) which is small if $p_T^{\rm miss}$ is caused by a single neutrino or undetected electron or photon, and can be large when there are two massive LSP's. The four-fermion processes cannot be entirely eliminated, however, and a non-negligible irreducible background is expected. Fortunately, the uncertainties for these backgrounds are not large.

High efficiencies are easily achieved when the mass of the LSP is lighter than the parent particle by at least 10 GeV/c^2 and greater than about 10 GeV/c^2. Difficulties arise when the mass difference ΔM between the produced particle and the LSP is smaller than 10 GeV/c^2 as the signal resembles background from two-photon interactions. A very light LSP is challenging also since, kinematically speaking, it plays a role similar to a neutrino, so that, for example, a signal for charginos of mass 80 GeV/c^2 is difficult to distinguish from the production of W^+W^- pairs.

Since the start of LEP 2, experimenters have made special efforts to cover a wide range of mass differences. Also, since virtual superpartners exchanged in decays can heavily influence branching ratios to SM particles, care has been taken to ensure that the search efficiencies are not strongly dependent on the final state. This ability to cover a wide range of topologies has driven the push for bounds with a minimum of model dependence.

Charginos have been excluded up to 86 GeV/c^2 [9] except in cases of low acceptance ($\Delta M = M_{\tilde{\chi}^\pm} - M_{\tilde{\chi}^0_1} \lesssim 5$ GeV/c^2) or low cross section ($M_{\tilde{\nu}_e} \lesssim M_W$). When $|\mu| \ll M_2$, the Higgsino components are large for charginos and neutralinos. In this case the associated production of neutralino pairs $\tilde{\chi}^0_1\tilde{\chi}^0_2$ is large and the problem of small mass differences ($M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$) less severe. Experimental sensitivity now extends down to mass differences of 4 GeV/c^2, corresponding to M_2 well above 1 TeV/c^2. The strong variation of the efficiency with ΔM makes it difficult to derive absolute bounds on the masses of charginos and neutralinos. The problem of low cross sections will be less severe after higher integrated luminosities have been delivered.

The limits from chargino and neutralino production are most often used to constrain M_2 and μ for fixed $\tan\beta$. An example from the OPAL Collaboration is shown in Fig. 1, where excluded regions in the (μ, M_2) plane are shown for $\tan\beta = 1.5$ and 35 for $\sqrt{s} = 172$ GeV. The case of heavy sneutrinos is illustrated by the plots with $m_0 = 1$ TeV/c^2. The plots also provide a gluino mass scale, valid assuming gaugino mass unification, which implies that the mass of gluinos hypothetically produced in proton machines is proportional to the mass of charginos with a large gaugino component.

When the sleptons are light, two important effects must be considered for charginos: the cross section is significantly reduced and the branching ratio to leptons is enhanced, especially to τ's via $\tilde{\tau}$'s which can have non-negligible mixing. These effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for $\mu \sim -70$ GeV/c^2

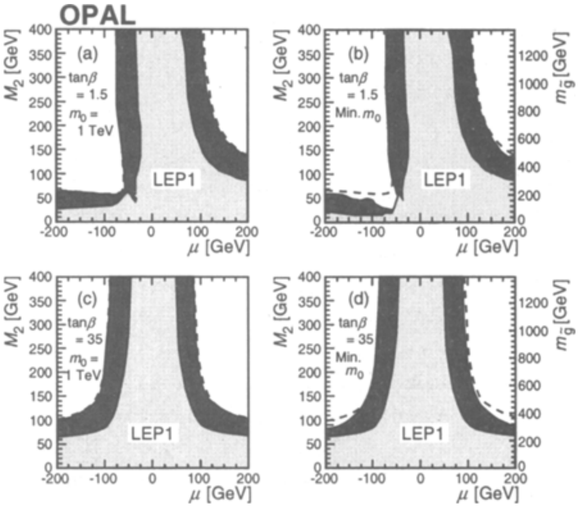

Figure 1: Regions in the (μ, M_2) plane excluded by chargino and neutralino searches performed by the OPAL Collaboration, for two values of $\tan\beta$ [9]. The light shaded region shows the limits derived from the Z width, while the dark region shows the additional exclusion obtained by the direct searches at LEP 2. The dashed line shows the kinematic bound for charginos; exclusions beyond this come from the searches for neutralinos. m_0 is the universal mass parameter for sleptons and sneutrinos, so when $m_0 = 1$ TeV/c^2 the sneutrino is very heavy and cross sections are as large as possible. The curves labeled 'minimal m_0' give an indication of how much the exclusions weaken when light sneutrinos are considered. The gluino scale is shown for comparison to Tevatron results; it is valid assuming the unification of gaugino masses.

and $\tan\beta < 2$, as the cross section is reduced with respect to larger $|\mu|$, the impact of $\widetilde{\tau}$ mixing can be large, and the efficiency is not optimal because ΔM is large. The erosion in the bounds when sneutrinos are light is illustrated clearly by the so-called 'minimal m_0' case (Fig. 1). Here m_0 is a universal mass for sleptons and sneutrinos at the GUT scale; for this analysis the smallest value of m_0 consistent with OPAL slepton limits has been taken.

If the sneutrino is lighter than the chargino, then two-body decays $\widetilde{\chi}^+ \to \ell^+\widetilde{\nu}$ dominate, and in the 'corridor' $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3$ GeV/c^2 the acceptance is so low that no exclusion is possible [10]. An example of this is shown in Fig. 2, from the ALEPH Collaboration. Since the chargino cross-section and field content varies with μ, two values were tested: in both cases the corridor $M_{\widetilde{\chi}^\pm} \lesssim M_{\widetilde{\nu}}$ persists, and strictly speaking the lower limit on $M_{\widetilde{\chi}^\pm}$ is the one from LEP 1. Searches for charged sleptons can be used to cover this corridor, as shown in the figure, but this coverage is effective only for low $\tan\beta$. The searches for neutralinos alleviate the problem in some regions of parameter space, but they cannot close the corridor.

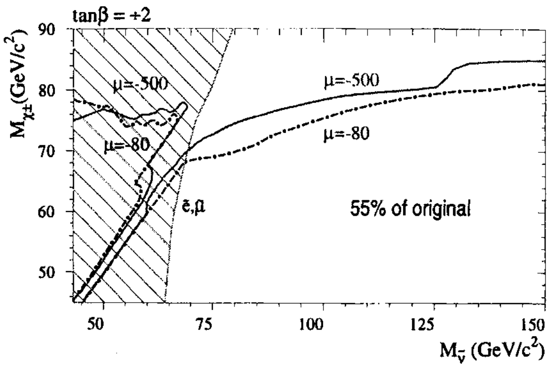

Figure 2: Limit on a gaugino-like chargino as a function of the sneutrino mass, from the ALEPH Collaboration [9]. The open corridor $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3$ GeV/c^2 i s evident. $\tan\beta = \sqrt{2}$ is fixed and two values of μ are shown. The hatched region is excluded by slepton searches, but at higher $\tan\beta$ this exclusion is much weaker.

The limits on slepton masses [11] are well below the kinematic limit due to a strong p-wave phase space suppression near threshold. A variety of limits have been derived, considering right-sleptons only (which is conservative), or degenerate right/left-sleptons (which is optimistic), or relying on a universal slepton mass m_0 (which is model-dependent). For individual experiments, the limits on selectrons reach 80 GeV/c^2 due to contributions from t-channel neutralino exchange; they depend slightly on μ and $\tan\beta$. For the extreme case $M_{\widetilde{\chi}^0_1} \to 0$, the AMY Collaboration at TRISTAN obtained a result which reaches 79 GeV/c^2 for degenerate selectrons at 90% CL [12]. Limits on smuons reach approximately 60 GeV/c^2, and staus, 55 GeV/c^2. For selectrons and smuons the dependence on $\Delta M = M_{\widetilde{\ell}} - M_{\widetilde{\chi}^0_1}$ is weak for $\Delta M \gtrsim 10$ GeV/c^2 unless parameters are chosen which lead to a large branching ratio for $\widetilde{\ell}_R \to \ell\widetilde{\chi}^0_2$, possible when $M_{\widetilde{\chi}^0_1}$ is very small. Preliminary results from the combination of the four LEP experiments have been derived, leading to significantly stronger bounds [13]: $M_{\widetilde{e}_R} > 80$ GeV/c^2 and $M_{\widetilde{\mu}_R} > 74$ GeV/c^2 for $M_{\widetilde{\chi}^0_1} = 45$ GeV/c^2. Bounds on the parameters M_2 and m_0 also have been derived.

In some GMSB models, sleptons may decay to $\ell^\pm \widetilde{g}_{3/2}$ outside the detector, so the experimental signature is a pair of colinear, heavily ionizing tracks. Searches for such events [14] have placed mass limits of 66 GeV/c^2 (combined: 68 GeV/c^2 [13]) for $\widetilde{\mu}_R$ and $\widetilde{\tau}_R$.

Limits on stop and sbottom masses [15], like the slepton mass limits, do not extend to the kinematic limit. The stop decay $\widetilde{t}_1 \rightarrow c\widetilde{\chi}_1^0$ proceeds through loops, giving a lifetime long enough to allow the top squark to form supersymmetric hadrons which provide a pair of jets and missing energy. If sneutrinos are light the decay $\widetilde{t}_1 \rightarrow b\ell\widetilde{\nu}$ dominates, giving two leptons in addition to the jets. Access to very small ΔM is possible due to the visibility of the decay products of the c and b quarks. Limits vary from 75 GeV/c^2 for an unrealistic pure $\widetilde{t}_L$ state to 60 GeV/c^2 if the coupling of $\widetilde{t}_1$ to the Z vanishes. The DELPHI result is shown in Fig. 3 as an example. The combination of results from all four experiments, shown in Fig. 4, is significantly stronger: for example, $M_{\widetilde{t}} > 75$ GeV/c^2 is obtained for $\Delta M > 10$ GeV/c^2 and *any* mixing [13]. Limits on sbottoms are weaker due to their smaller electric charge.

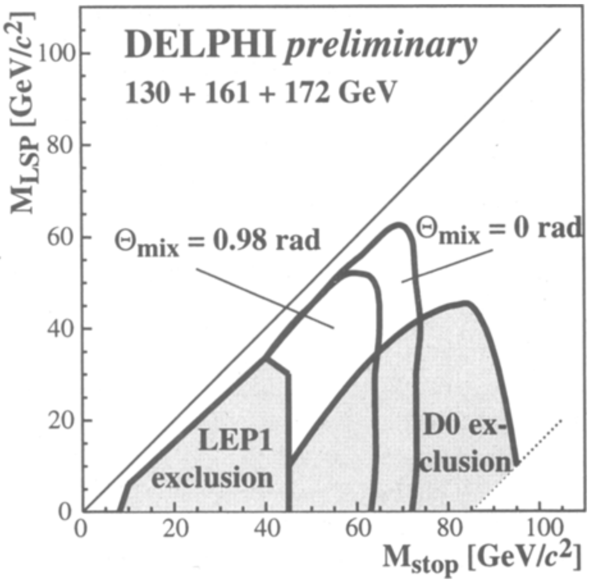

Figure 3: Ranges of excluded stop and neutralino masses reported by the DELPHI Collaboration [15]. Two values of mixing angle are shown: $\theta_{\rm mix} = 0$ gives pure $\widetilde{t}_L$ and $\theta_{\rm mix} = 0.98$ rad gives a stop with no coupling to the Z. The range excluded by DØ is also shown.

In canonical SUSY scenarios the lightest neutralino leaves no signal in the detector. Nonetheless, the tight correspondences among the neutralino and chargino masses allow an indirect limit on $M_{\widetilde{\chi}_1^0}$ to be derived [9,10]. The key assumption is that the gaugino mass parameters M_1 and M_2 unify at the GUT scale, which leads to a definite relation between them at the electroweak scale: $M_1 = \frac{5}{3}\tan^2\theta_W M_2$. Assuming slepton masses to be at least 200 GeV/c^2, the bound on $M_{\widetilde{\chi}_1^0}$ is derived from the results of chargino and neutralino searches and certain bounds from LEP 1, as illustrated in Fig. 5, from DELPHI. The various contours change as $\tan\beta$ is increased, with the result that the lower limit on $M_{\widetilde{\chi}_1^0}$ increases also.

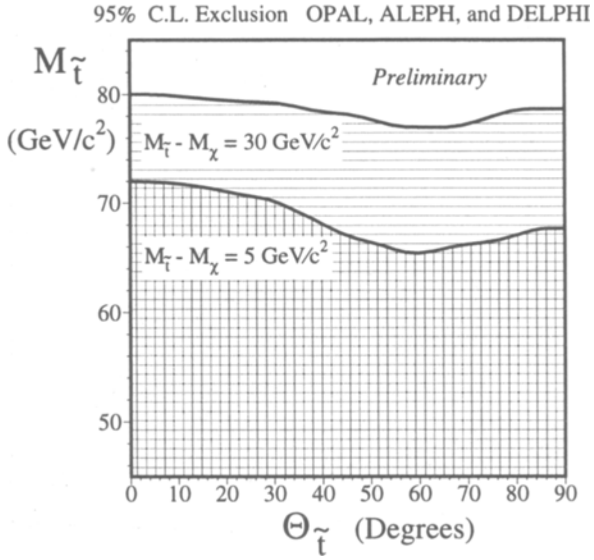

Figure 4: Lower bound on the stop mass as a function of the mixing angle for two values of $\Delta M = M_{\widetilde{t}} - M_{\widetilde{\chi}_1^0}$, derived from the combined results of the LEP experiments. These results are preliminary [13].

When sleptons are lighter than 80 GeV/c^2, all the effects of light sneutrinos on both the production and decay of charginos and heavier neutralinos must be taken into account. Although the bounds from charginos are weakened substantially, useful additional constraints from the slepton searches rule out the possibility of a massless neutralino. The current *preliminary* limit, shown in Fig. 6, is $M_{\widetilde{\chi}_1^0} > 25$ GeV/c^2 for $\tan\beta > 1$ and $M_{\widetilde{\nu}} > 200$ GeV/c^2 (effectively, $m_0 \gtrsim 200$ GeV/c^2). Allowing the universal slepton mass m_0 to have any value, the limit is $M_{\widetilde{\chi}_1^0} > 14$ GeV/c^2 [10]. These bounds can be evaded by dropping gaugino mass unification or R-parity conservation, or by assuming the gluino is very light.

If R-parity is not conserved, the lightest neutralino decays to SM particles and is visible inside the detector. Searches for supersymmetry with R-parity violation [16] usually assume that one of three possible interaction terms ($LL\overline{E}$, $LQ\overline{D}$, $\overline{U}\,\overline{D}\,\overline{D}$) dominates. The relevant term can cause R-parity violation *directly* in the decay of the produced particle, or it can be manifested *indirectly* in the decay of the LSP, which need no longer be neutral or colorless. Rather exotic topologies can occur, such as six-lepton final states in slepton production with $LL\overline{E}$ dominating, or ten-jet final states in chargino production with $\overline{U}\,\overline{D}\,\overline{D}$ dominating; and, for the most part, entirely new search criteria keyed to an excess of leptons and/or jets must be devised. Although not all possibilities have been tested yet, searches with a wide scope have found no evidence for supersymmetry with R-parity violation, and limits are usually

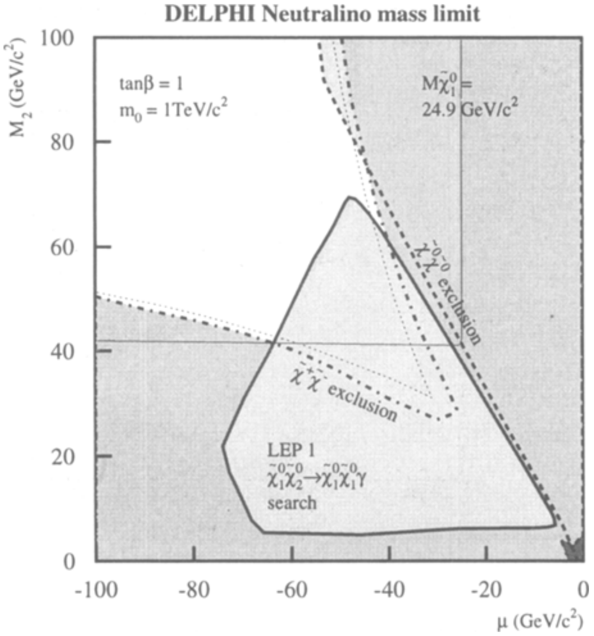

Figure 5: Excluded regions in the (μ, M_2) plane obtained by the DELPHI Collaboration, for $\tan\beta = 1$ and $m_0 = 1$ TeV/c^2 [9]. (This very high value for m_0 is tantamount to setting all slepton masses to 1 TeV/c^2.) The combination of LEP 2 chargino search (dot-dash line) and the neutralino search (dashed line) with the single-photon limits from LEP 1 (thick solid line) give the limit on $M_{\widetilde{\chi}^0_1}$. The thin solid line shows the values of μ and M_2 giving $M_{\widetilde{\chi}^0_1} = 24.9$ GeV/c^2, and the dotted line gives the kinematic limit for charginos at $\sqrt{s} = 172$ GeV.

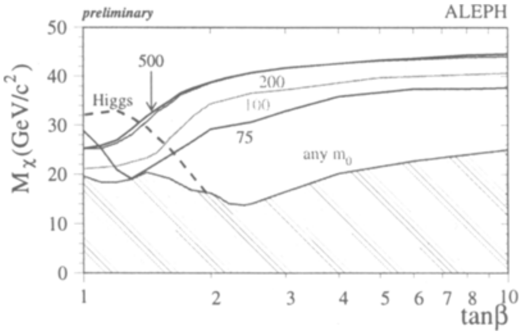

Figure 6: Lower limit on the mass of the lightest neutralino, derived by the ALEPH Collaboration using constraints from chargino, neutralino, and slepton searches [10]. The values $500, \ldots, 75$ show the bound obtained when fixing the universal scalar mass and taking slepton bounds into account; including also limits from Higgs for $m_0 = 75$ GeV/c^2 gives the dashed line. Allowing m_0 to vary freely independently of $\tan\beta$ gives the curve labelled 'any m_0.'

as constraining as in the canonical scenario. In fact, the direct exclusion of pair-produced $\widetilde{\chi}^0_1$'s rules out some parameter space not accessible in the canonical case.

R-parity violation can lead to new production processes, such as s-channel sneutrino production, which also are being investigated [17].

Visible signals from the lightest neutralino are also realized in special cases of GMSB which predict $\widetilde{\chi}^0_1 \to \gamma \widetilde{g}_{3/2}$ with a lifetime short enough for the decay to occur inside the detector. The most promising topology consists of two energetic photons and missing energy resulting from $e^+e^- \to \widetilde{\chi}^0_1\widetilde{\chi}^0_1$. (In the canonical scenario, such events also would appear for $e^+e^- \to \widetilde{\chi}^0_2\widetilde{\chi}^0_2$ followed by $\widetilde{\chi}^0_2 \to \gamma\widetilde{\chi}^0_1$ which can be expected in certain regions of parameter space.) The LEP experiments have observed no excess over the expected number of background events [18], leading to a bound on the neutralino mass of about 70 GeV/c^2. As an example, the L3 upper limit on the number of signal events is plotted as a function of neutralino mass in Fig. 7. When the results are combined [13], the limit is $M_{\widetilde{\chi}^0_1} > 75$ GeV/c^2. Single-photon production has been used to constrain the process $e^+e^- \to \widetilde{g}_{3/2}\widetilde{\chi}^0_1$.

At the time of this writing, LEP was colliding beams at $\sqrt{s} = 183$ GeV. No signals for supersymmetry were reported in conferences; rather, preliminary limits $M_{\widetilde{\chi}^\pm} \gtrsim 91$ GeV/c^2 were shown [19]. In coming years the center of mass energy will be increased in steps up to a maximum of 200 GeV.

II.5. Supersymmetry searches at proton machines: Although the LEP experiments can investigate a wide range of scenarios and cover obscure corners of parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Each experiment has logged approximately 110 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV—ten times the energy of LEP 2. Although the full energy is never available for annihilation, the cross sections for supersymmetric particle production are large due to color factors and the strong coupling.

The main source of signals for supersymmetry are squarks (scalar partners of quarks) and gluinos (fermionic partners of gluons), in contradistinction to LEP. Pairs of squarks or gluinos are produced in s, t and u-channel processes, which decay directly or via cascades to at least two LSP's. The key distinction in the experimental signature is whether the gluino is heavier or lighter than the squarks, with the latter occurring naturally in mSUGRA models. The u, d, s, c, and b squarks are assumed to have similar masses; the search results are reported in terms of their average mass $M_{\widetilde{q}}$ and the gluino mass $M_{\widetilde{g}}$.

The classic searches [20] rely on large missing transverse energy $\not{E}_T$ caused by the escaping neutralinos. Jets with high

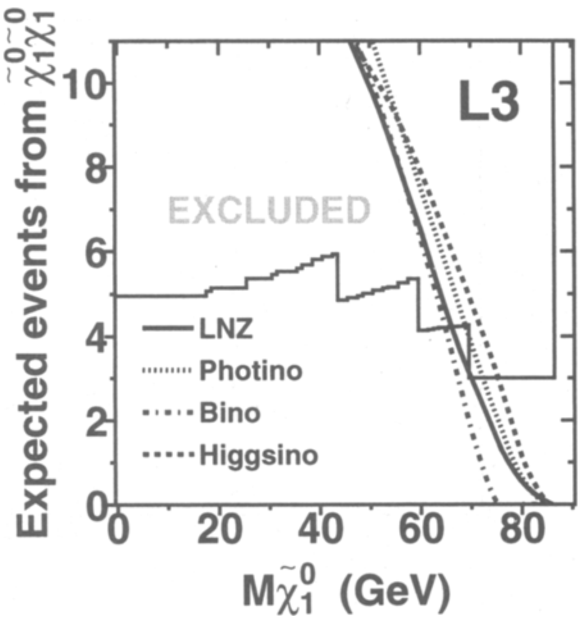

Figure 7: Upper limit on the number of acoplanar photon events as a function of the neutralino mass, from the L3 Collaboration [18]. The theoretical cross section depends on the field content of the neutralino, shown here for pure photinos, binos, and Higgsinos. 'LNZ' refers to a particular model [4].

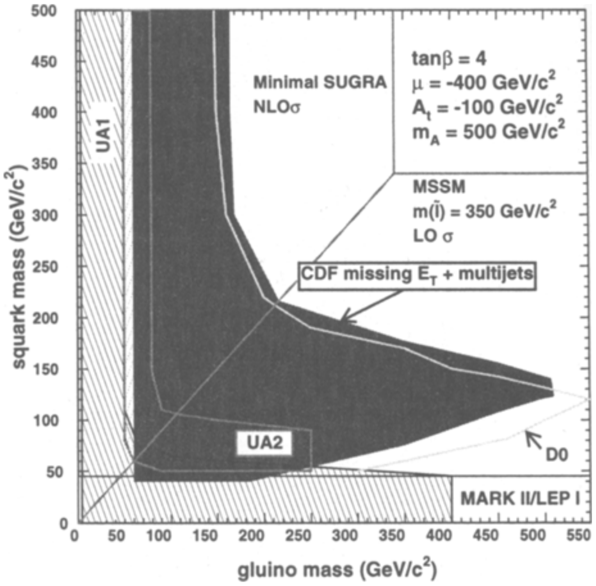

Figure 8: Excluded ranges of squark and gluino masses, derived from the jets+ $\not\!\!E_T$ analysis of the CDF Collaboration [20]. Also shown are recent results from DØ, and much older limits from the CERN proton experiments UA1 and UA2.

transverse energy are also required as evidence of a hard interaction; care is taken to distinguish genuine $\not\!\!E_T$ from fluctuations in the jet energy measurement. Backgrounds from W, Z and top production are reduced by rejecting events with identified leptons. Uncertainties in the rates of these processes are minimized by normalizing related samples, such as events with two jets and one or more leptons. The tails of more ordinary hard-scattering processes accompanied by multiple gluon emission are estimated directly from the data.

The bounds are displayed in the $(M_{\tilde g}, M_{\tilde q})$ plane and have steadily improved with the integrated luminosity. The latest result from the CDF Collaboration is shown in Fig. 8, which also shows a recent result from DØ. If the squarks are heavier than the gluino, then $M_{\tilde g} \gtrsim 180$ GeV/c^2. If they all have the same mass, then that mass is at least 260 GeV/c^2, according to the DØ analysis. If the squarks are much lighter than the gluin (in which case they decay via $\tilde q \to q\tilde\chi_1^0$), the bounds from UA1 and UA2 [21] play a role giving $M_{\tilde g} \gtrsim 300$ GeV/c^2. All of these bounds assume there is no gluino lighter than 5 GeV/c^2.

Since these results are expressed in terms of the physical masses relevant to the production process and experimental signature, the excluded region depends primarily on the assumption of nearly equal squark masses with only a small dependence on other parameters such as μ and $\tan\beta$. Direct constraints on the theoretical parameters m_0 and $m_{1/2} \approx 0.34\,M_3$, shown in Fig. 9, have been obtained by the DØ Collaboration assuming the mass relations of the mSUGRA model. In particular, m_0 is keyed to the squark mass and $m_{1/2}$ to the gluino mass, while for the LEP results these parameters usually relate to slepton and chargino masses.

Charginos and neutralinos may be produced directly by annihilation ($q\bar q \to \tilde\chi_i^\pm\tilde\chi_j^0$) or in the decays of heavier squarks ($\tilde q \to q'\tilde\chi_i^\pm$, $q\tilde\chi_j^0$). They decay to energetic leptons (for example, $\tilde\chi^\pm \to \ell\nu\tilde\chi_1^0$ and $\tilde\chi_2^0 \to \ell^+\ell^-\tilde\chi_1^0$) and the branching ratio can be high for some parameter choices. The presence of energetic leptons has been exploited in two ways: the 'trilepton' signature and the 'dilepton' signature.

The search for trileptons is most effective for the associated production of $\tilde\chi_1^\pm\tilde\chi_2^0$ [22]. The requirement of three energetic leptons reduces backgrounds to a very small level, but is efficient for the signal only in special cases. The results reported to date are not competitive with the LEP bounds.

The dilepton signal is geared more for the production of charginos in gluino and squark cascades [23]. Jets are required as expected from the rest of the decay chain; the leptons should be well separated from the jets in order to avoid backgrounds from heavy quark decays. Drell-Yan events are rejected with simple cuts on the relative azimuthal angles of the leptons and their transverse momentum. In some analyses the Majorana nature of the gluino is exploited by requiring two leptons with

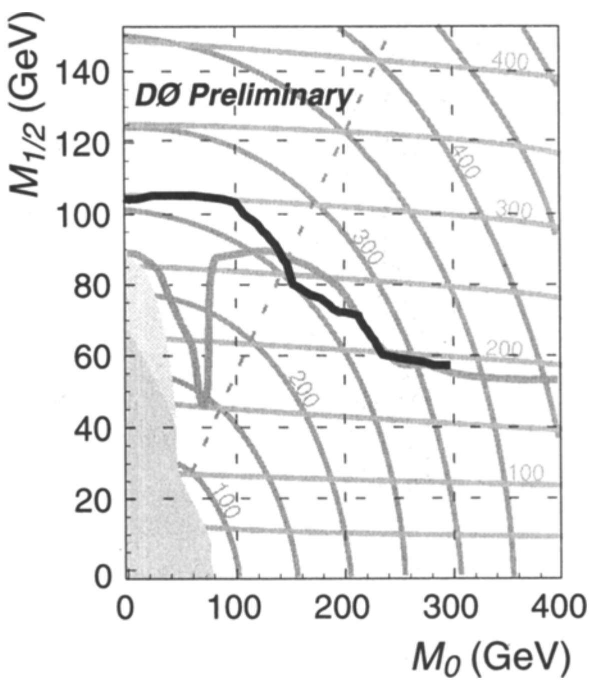

Figure 9: Bounds in the $(m_0, m_{1/2})$ plane obtained by the DØ Collaboration from their searches for squarks and gluinos [20]. The dark solid line shows the result from the jets+ $\not\!\!E_T$ selection, and the grey solid line shows the result from the dielectron selection. The radial contours give the squark mass in this plane, and the nearly horizontal lines give the gluino mass. Parameter values in the shaded region lead to unphysical conditions.

the same charge, thereby greatly reducing the background. In this scenario limits on squarks and gluinos are almost as stringent as in the classic jets+ $\not\!\!E_T$ case.

It should be noted that the dilepton search complements the multijet+ $\not\!\!E_T$ search in that the acceptance for the latter is reduced when charginos and neutralinos are produced in the decay cascades—exactly the situation in which the dilepton signature is most effective.

A loophole in the squark-gluino bounds has recently been addressed using dijet mass distributions [24]. If gluinos are lighter than about 5 GeV/c^2, $\not\!\!E_T$ is very small and the classic jets+ $\not\!\!E_T$ searches are no longer effective. Resonant production of squarks would have a large cross section, however, and if the squarks are not very heavy, broad peaks in the dijet mass distributions are expected. Comparison of the observed spectrum with theoretical estimates rules out light gluinos if squarks are lighter than about 600 GeV/c^2.

The top squark is different from the other squarks because its SM partner is so massive: large off-diagonal terms in the squared-mass matrix lead to large mixing effects and a possible light mass eigenstate, $M_{\widetilde{t}_1} \ll M_{\widetilde{q}}$. Analyses designed to find light stops have been performed by DØ [25]. The first of these was based on the jets+ $\not\!\!E_T$ signature expected when the the stop is lighter than the chargino. A powerful limit $M_{\widetilde{t}} \gtrsim 90$ GeV/c^2 was obtained, provided the neutralino was at least 30 GeV/c^2 lighter than the stop as depicted in Fig. 3. (These searches are sensitive to the $c\widetilde{\chi}_1^0$ channel which does not apply below the dotted line.) More recently a search for the pair-production of light stops decaying to $b\widetilde{\chi}_1^\pm$ was performed. The presence of two energetic electrons was required; backgrounds from W's were greatly reduced. Regrettably this experimental bound does not yet improve existing bounds on stop masses.

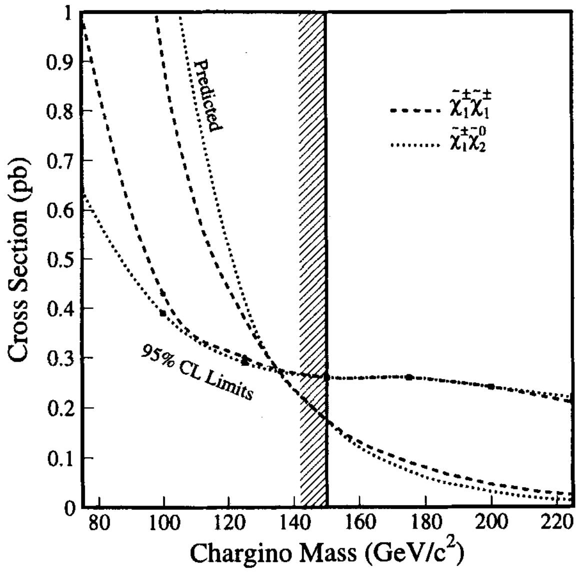

Figure 10: Comparison of the DØ upper limits on chargino and neutralino cross sections with theory in a GMSB scenario, plotted as a function of the chargino mass [28]. The vertical line shows the result obtained from the combined chargino and neutralino exclusions. It corresponds to $M_{\widetilde{\chi}_1^0} \gtrsim 75$ GeV/c^2.

An anomalous event observed by the CDF Collaboration [26] sparked much theoretical speculation [27]. It contains two energetic electrons, two energetic photons, large $\not\!\!E_T$, and little else. Since it is difficult to explain this event with SM processes, theorists have turned to SUSY. While some models are based on canonical MSSM scenarios (without gaugino mass unification), others are based on GMSB models with selectron production followed by $\widetilde{e} \to e\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^0 \to \gamma\,\widetilde{g}_{3/2}$. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic constraints derived from the properties of the CDF event. The Tevatron experiments have looked for such events, and have found none [28], aside from the one anomalous event. These results have been translated into the bound $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2, as shown in Fig. 10 from the DØ Collaboration. This bound is

Table 1: Lower limits on supersymmetric particle masses. 'GMSB' refers to models with gauge-mediated supersymmetry breaking, and 'RPV' refers to models allowing R-parity violation.

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^\pm$	gaugino	$M_{\widetilde{\nu}} > 200$ GeV/c^2	86	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^\pm}$	67	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$ TeV/c^2	79	LEP 2
	GMSB		150	D0 isolated photons
	RPV	$LL\overline{E}$ worst case	73	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ GeV/c^2	83	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 200$ GeV/c^2	25	LEP 2
		any $\tan\beta$, any m_0	14	LEP 2
	GMSB		75	D0 and LEP 2
	RPV	$LL\overline{E}$ worst case	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	75	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	75	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20$ GeV/c^2	53	LEP 2
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	76	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any θ_{mix}, $\Delta M > 10$ GeV/c^2	70	LEP 2 combined
		any θ_{mix}, $M_{\widetilde{\chi}_1^0} < \frac{1}{2}M_{\widetilde{t}}$	86	D0
	$b\ell\widetilde{\nu}$	any θ_{mix}, $\Delta M > 7$ GeV/c^2	64	LEP 2 combined
$\widetilde{g}$	any $M_{\widetilde{q}}$		190	D0 jets+$\not{E}_T$
			180	CDF dileptons
$\widetilde{q}$	$M_{\widetilde{q}} = M_{\widetilde{g}}$		260	D0 jets+$\not{E}_T$
			230	CDF dileptons

as good as that derived from the combination of the four LEP experiments.

II.6. Supersymmetry searches at HERA and fixed-target experiments: The electron-proton collider (HERA) at DESY runs at $\sqrt{s} = 310$ GeV and, due to its unique beam types, can be used to probe certain channels more effectively than LEP or the Tevatron.

The first of these is associated selectron-squark production [29] through t-channel neutralino exchange. Assuming the conservation of R-parity, the signal consists of an energetic isolated electron, a jet, and missing transverse momentum. No signal was observed in 20 pb^{-1} of data and limits were placed on the sum $\frac{1}{2}(M_{\widetilde{e}} + M_{\widetilde{q}})$. They are weaker than the latest ones from LEP.

A more interesting opportunity comes in SUSY models with R-parity violation, in particular, with a dominant $LQ\overline{D}$ interaction [30]. Squarks would be produced directly in the s-channel, decaying either directly to a lepton and a quark via R-parity violation or to a pair of fermions and a chargino or neutralino, with the latter possibly decaying via R-parity violation. Less than 3 pb^{-1} were used to look for a squark resonance above SM backgrounds. All possible topologies were considered, so model-independent bounds on the R-parity-violating parameter λ'_{111} could be derived as a function of the squark mass. The special case of a light $\widetilde{t}_1$ was also considered, and limits derived on λ'_{131} as a function of $M_{\widetilde{t}}$. These were improved by considering also the pair-production of stops via photon-gluon fusion (see the Listings for more information).

Limits from SUSY searches in fixed-target or beam-dump experiments were surpassed long ago by the colliders. An important exception is the search for the light gluino, materializing as a long-lived supersymmetric hadron called the R^0 [6]. These could be produced in fixed-target experiments with hadron beams and observed via their decay in flight to a low mass hadronic state: $R^0 \to \pi^+\pi^-\widetilde{\chi}_1^0$ or $\eta\widetilde{\chi}_1^0$. The KTeV Collaboration at Fermilab have searched for R^0's in their neutral-kaon data and found no evidence for this particle in the $\pi^+\pi^-\widetilde{\chi}_1^0$ channel, deriving strong limits on its mass and lifetime [31], as shown in Fig. 11. A complementary search for supersymmetric baryons was performed by the E761 Collaboration with a charged hyperon beam [32].

II.7. Conclusions: A huge variety of searches for supersymmetry have been carried out at LEP, the Tevatron, and HERA. Despite all the effort, no signal has been found, forcing the

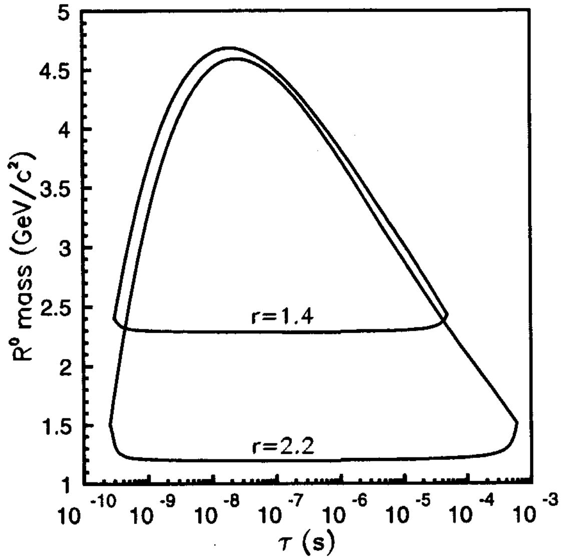

Figure 11: Ranges of R^0 mass and lifetime excluded at 90% CL by the KTeV Collaboration [31]. The ratio of the R^0 to the $\widetilde{\chi}_1^0$ mass is r.

experimenters to derive limits. We have tried to summarize the interesting cases in Table 1. At the present time there is little room for SUSY particles lighter than M_W. The LEP collaborations will analyze more data taken at higher energies, and the Tevatron collaborations will begin a high luminosity run in a couple of years. If still no sign of supersymmetry appears, definitive tests will be made at the LHC.

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   L3: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 522;
   OPAL: CERN-PPE/97-083;
   L3: CERN-PPE/97-130.
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    DELPHI: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 353;
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15. **ALEPH**: CERN-PPE/97-084;
    OPAL: CERN-PPE/97-046.
16. **ALEPH**: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 621;
    DELPHI: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 589;

OPAL: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 213;
ALEPH: Phys. Lett. **B384**, 461 (1996) and Phys. Lett. **B349**, 238 (1995);
OPAL: Phys. Lett. **B313**, 333 (1993).

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DELPHI: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 467.
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DELPHI: CERN-PPE/97-107;
L3: CERN-PPE/97-076.
19. **L3**: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 859;
DELPHI: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 858;
ALEPH: *EPS-HEP Conf.*, Jerusalem (1997) Ref. 856.
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CDF: Fermilab Conf-96/371-E;
DØ: Phys. Rev. Lett. **76**, 2228 (1996);
CDF: Phys. Rev. Lett. **76**, 4307 (1996).
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H1: Phys. Lett. **B380**, 461 (1996).
30. **H1**: Z. Phys. **C71**, 211 (1996).
31. **KTeV**: preprint Rutgers-97-26, hep-ex/9709028.
32. **E761**: Phys. Rev. Lett. **78**, 3252 (1997).

MINIMAL SUPERSYMMETRIC STANDARD MODEL ASSUMPTIONS

All results shown below (except where stated otherwise) are based on the Minimal Supersymmetric Standard Model (MSSM) as described in the Note on Supersymmetry. This includes the assumption that R-parity is conserved. In addition the following assumptions are made in most cases:

1) The $\widetilde{\chi}^0_1$ (or $\widetilde{\gamma}$) is the lightest supersymmetric particle (LSP).

2) $m_{\widetilde{f}_L} = m_{\widetilde{f}_R}$ where $\widetilde{f}_L$ and $\widetilde{f}_R$ refer to the scalar partners of left-and right-handed fermions.

Limits involving different assumptions either are identified with comments or are in the miscellaneous section.

When needed, specific assumptions of the eigenstate content of neutralinos and charginos are indicated (use of the notation $\widetilde{\gamma}$ (photino), $\widetilde{H}$ (Higgsino), $\widetilde{W}$ (w-ino), and $\widetilde{Z}$ (z-ino) indicates the approximation of a pure state was made).

$\widetilde{\chi}^0_1$ (Lightest Neutralino) MASS LIMIT

$\widetilde{\chi}^0_1$ is likely to be the lightest supersymmetric particle (LSP). See also the $\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ section below.

We have divided the $\widetilde{\chi}^0_1$ listings below into three sections: 1) Accelerator limits for $\widetilde{\chi}^0_1$, 2) Bounds on $\widetilde{\chi}^0_1$ from dark matter searches, and 3) Other bounds on $\widetilde{\chi}^0_1$ from astrophysics and cosmology.

Accelerator limits for $\widetilde{\chi}^0_1$

These papers generally exclude regions in the $M_2-\mu$ parameter plane based on accelerator experiments. Unless otherwise stated, these papers assume minimal supersymmetry and GUT relations (gaugino-mass unification condition). $\Delta m_0 = m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>24.9	95	[1] ABREU	98	DLPH	
>10.9	95	[2] ACCIARRI	98F	L3	$\tan\beta > 1$
>13.3	95	[3] ACKERSTAFF	98L	OPAL	$\tan\beta > 1$
>12.5	95	[4] ALEXANDER	96L	OPAL	$\tan\beta > 1.5$
>12.8	95	[5] BUSKULIC	96A	ALEP	$m_{\widetilde{\nu}} > 200$ GeV
>23	95	[6] ACCIARRI	95E	L3	$\tan\beta > 3$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>17	95	[7] ELLIS	97C	RVUE	All $\tan\beta$
		[8] ABREU	96O	DLPH	
		[9] ACCIARRI	96F	L3	
>12.0	95	[10] ALEXANDER	96J	OPAL	$1.5 < \tan\beta < 35$
≥ 0		[11] FRANKE	94	RVUE	$\widetilde{\chi}^0_1$ mixed with a singlet
>20	95	[12] DECAMP	92	ALEP	$\tan\beta > 3$
>5	90	[13] HEARTY	89	ASP	$\widetilde{\gamma}$; for $m_{\widetilde{e}} < 55$ GeV

[1] ABREU 98 bound combines the chargino and neutralino searches at $\sqrt{s}$=161, 172 GeV with single-photon-production results at LEP-1 from ABREU 97J. The limit is based on the same assumptions as ALEXANDER 96J except m_0=1 TeV.

[2] ACCIARRI 98F evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The limit is obtained for $0 < M_2 < 2000$, $|\mu| < 500$, and $1 < \tan\beta < 40$, but remains valid outside this domain. No dependence on the trilinear-coupling parameter A is found. The limit holds for all values of m_0 consistent with scalar lepton contraints. It improves to 24.6 GeV for $m_{\widetilde{\nu}} > 200$ GeV. Data taken at $\sqrt{s}$ = 130–172 GeV.

[3] ACKERSTAFF 98L evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The bound is determined indirectly from the $\widetilde{\chi}^+_1$ and $\widetilde{\chi}^0_2$ searches within the MSSM. The limit is obtained for $0 < M_2 < 1500$, $|\mu| < 500$ and $\tan\beta > 1$, but remains valid outside this domain. The limit holds for the smallest value of m_0 consistent with scalar lepton constraints (ACKERSTAFF 97H). It improves to 24.7 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$=130–172 GeV.

[4] ALEXANDER 96L bound for $\tan\beta$=35 is 26.0 GeV.

[5] BUSKULIC 96A puts a lower limit on $m_{\widetilde{\chi}^0_1}$ from the negative search for neutralinos, charginos. The bound holds for $m_{\widetilde{\nu}} > 200$ GeV. A small region of (μ,M_2) still allows $m_{\widetilde{\chi}^0_1}$=0 if sneutrino is lighter. This analysis combines data from e^+e^- collisions at $\sqrt{s}$=91.2 and at 130–136 GeV.

[6] ACCIARRI 95E limit for $\tan\beta > 2$ is 20 GeV, and the bound disappears if $\tan\beta \sim 1$.

[7] ELLIS 97C uses constraints on $\chi^{\pm}$, χ^0, and $\widetilde{\ell}$ production obtained by the LEP experiments from e^+e^- collisions at $\sqrt{s}$ = 130–172 GeV. It assumes a universal mass m_0 for scalar leptons at the grand unification scale.

[8] ABREU 96O searches for possible final states of neutralino pairs produced in e^+e^- collisions at $\sqrt{s}$ = 130–140 GeV. See their Fig. 3 for excluded regions in the (μ,M_2) plane.

[9] ACCIARRI 96F searches for possible final states of neutralino pairs produced in e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 5 for excluded regions in the (μ,M_2) plane.

[10] ALEXANDER 96J bound is determined indirectly from the $\widetilde{\chi}^{\pm}_1$ and $\widetilde{\chi}^0_2$ searches within MSSM. A universal scalar mass m_0 at the grand unification scale is assumed. The bound is for the smallest possible value of m_0 allowed by the LEP $\widetilde{\ell}$, $\widetilde{\nu}$ mass limits. Branching fractions are calculated using minimal supergravity. The bound is for $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} > 10$ GeV. The limit improves to 21.4 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136

GeV. ACKERSTAFF 96C, using data from $\sqrt{s} = 161$ GeV, improves the limit for $m_0 =$ 1 TeV to 30.3 GeV.

[11] FRANKE 94 reanalyzed the LEP constraints on the neutralinos in the MSSM with an additional singlet.

[12] DECAMP 92 limit for $\tan\beta > 2$ is $m > 13$ GeV.

[13] HEARTY 89 assumed pure $\widetilde{\gamma}$ eigenstate and $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$. There is no limit for $m_{\widetilde{e}} > 58$ GeV. Uses $e^+ e^- \rightarrow \gamma\widetilde{\gamma}\widetilde{\gamma}$. No GUT relation assumptions are made.

Bounds on $\widetilde{\chi}^0_1$ from dark matter searches

These papers generally exclude regions in the $M_2 - \mu$ parameter plane assuming that $\widetilde{\chi}^0_1$ is the dominant form of dark matter in the galactic halo. These limits are based on the lack of detection in laboratory experiments or by the absence of a signal in underground neturino detectors. The latter signal is expected if $\widetilde{\chi}^0_1$ accumlates in the Sun or the Earth and annihilates into high-energy ν's.

VALUE	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[14] BOTTINO 97	DAMA
	[15] LOSECCO 95	RVUE
	[16] MORI 93	KAMI
	[17] BOTTINO 92	COSM
	[18] BOTTINO 91	RVUE
	[19] GELMINI 91	COSM
	[20] KAMIONKOW..91	RVUE
	[21] MORI 91B	KAMI
none 4–15 GeV	[22] OLIVE 88	COSM

[14] BOTTINO 97 points out that the current data from the dark-matter detection experiment DAMA are sensitive to neutralinos in domains of parameter space not excluded by terrestrial laboratory searches.

[15] LOSECCO 95 reanalyzed the IMB data and places lower limit on $m_{\widetilde{\chi}^0_1}$ of 18 GeV if the LSP is a photino and 10 GeV if the LSP is a higgsino based on LSP annihilation in the sun producing high-enery neutrinos and the limits on neutrino fluxes from the IMB detector.

[16] MORI 93 excludes some region in M_2–μ parameter space depending on $\tan\beta$ and lightest scalar Higgs mass for neutralino dark matter $m_{\widetilde{\chi}^0} > m_W$, using limits on upgoing muons produced by energetic neutrinos from neutralino annihilation in the Sun and the Earth.

[17] BOTTINO 92 excludes some region M_2-μ parameter space assuming that the lightest neutralino is the dark matter, using upgoing muons at Kamiokande, direct searches by Ge detectors, and by LEP experiments. The analysis includes top radiative corrections on Higgs parameters and employs two different hypotheses for nucleon-Higgs coupling. Effects of rescaling in the local neutralino density according to the neutralino relic abundance are taken into account.

[18] BOTTINO 91 excluded a region in $M_2 - \mu$ plane using upgoing muon data from Kamioka experiment, assuming that the dark matter surrounding us is composed of neutralinos and that the Higgs boson is not too heavy.

[19] GELMINI 91 exclude a region in $M_2 - \mu$ plane using dark matter searches.

[20] KAMIONKOWSKI 91 excludes a region in the M_2–μ plane using IMB limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the sun, assuming that the dark matter is composed of neutralinos and that $m_{H^0_1} \lesssim 50$ GeV. See Fig. 8 in the paper.

[21] MORI 91B exclude a part of the region in the M_2–μ plane with $m_{\widetilde{\chi}^0_1} \lesssim 80$ GeV using a limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the earth, assuming that the dark matter surrounding us is composed of neutralinos and that $m_{H^0_1} \lesssim 80$ GeV.

[22] OLIVE 88 result assumes that photinos make up the dark matter in the galactic halo. Limit is based on annihilations in the sun and is due to an absence of high energy neutrinos detected in underground experiments. The limit is model dependent.

Other bounds on $\widetilde{\chi}^0_1$ from astrophysics and cosmology

Most of these papers generally exclude regions in the $M_2 - \mu$ parameter plane by requiring that the $\widetilde{\chi}^0_1$ contribution to the overall cosmological density is less than some maximal value to avoid overclosure of the Universe. Those not based on the cosmological density are indicated. Many of these papers also include LEP and/or other bounds.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>40		[23] ELLIS 97C	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>21.4	95	[24] ELLIS 96B	RVUE	$\tan\beta > 1.2$, $\mu < 0$
		[25] FALK 95	COSM	*CP*-violating phases
		DREES 93	COSM	Minimal supergravity
		FALK 93	COSM	Sfermion mixing
		KELLEY 93	COSM	Minimal supergravity
		MIZUTA 93	COSM	Co-annihilation
		ELLIS 92F	COSM	Minimal supergravity
		KAWASAKI 92	COSM	Minimal supergravity, $m_0 = A = 0$
		LOPEZ 92	COSM	Minimal supergravity, $m_0 = A = 0$
		MCDONALD 92	COSM	
		NOJIRI 91	COSM	Minimal supergravity
		[26] OLIVE 91	COSM	
		ROSZKOWSKI 91	COSM	
		ELLIS 90	COSM	
		[27] GRIEST 90	COSM	
		[28] GRIFOLS 90	ASTR	$\widetilde{\gamma}$; SN 1987A
		KRAUSS 90	COSM	
		[26] OLIVE 89	COSM	
> 100 eV		[29] ELLIS 88B	ASTR	$\widetilde{\gamma}$; SN 1987A
none 100 eV – (5–7) GeV		SREDNICKI 88	COSM	$\widetilde{\gamma}$; $m_{\widetilde{f}} = 60$ GeV
none 100 eV – 15 GeV		SREDNICKI 88	COSM	$\widetilde{\gamma}$; $m_{\widetilde{f}} = 100$ GeV
none 100 eV–5 GeV		ELLIS 84	COSM	$\widetilde{\gamma}$; for $m_{\widetilde{f}} = 100$ GeV
		GOLDBERG 83	COSM	$\widetilde{\gamma}$
		[30] KRAUSS 83	COSM	$\widetilde{\gamma}$
		VYSOTSKII 83	COSM	$\widetilde{\gamma}$

[23] ELLIS 97C uses in addition to cosmological constraints, data from $e^+ e^-$ collisions at 170–172 GeV. It assumes a universal scalar mass for both the Higgs and scalar leptons, as well as radiative supersymmetry breaking with universal gaugino masses. ELLIS 97C also uses the absence of Higgs detection (with the assumptions listed above) to set a limit on $\tan\beta > 1.7$ for $\mu < 0$ and $\tan\beta > 1.4$ for $\mu > 0$. This paper updates ELLIS 96B.

[24] ELLIS 96B uses, in addition to cosmological constraints, data from BUSKULIC 96K and SUGIMOTO 96. It assumes a universal scalar mass m_0 and radiative Supersymmetry breaking, with universal gaugino masses.

[25] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim 350$ GeV for $m_t = 174$ GeV.

[26] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim 350$ GeV for $m_t \leq 200$ GeV. Mass of the higgsino (=LSP) is limited to $m_{\widetilde{H}} \lesssim 1$ TeV for $m_t \leq 200$ GeV.

[27] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim 550$ GeV. Mass of the higgsino (=LSP) is limited to $m_{\widetilde{H}} \lesssim 3.2$ TeV.

[28] GRIFOLS 90 argues that SN1987A data exclude a light photino ($\lesssim 1$ MeV) if $m_{\widetilde{q}} < 1.1$ TeV, $m_{\widetilde{e}} < 0.83$ TeV.

[29] ELLIS 88B argues that the observed neutrino flux from SN 1987A is inconsistent with a light photino if 60 GeV $\lesssim m_{\widetilde{q}} \lesssim$ 2.5 TeV. If m(higgsino) is O(100 eV) the same argument leads to limits on the ratio of the two Higgs v.e.v.'s. LAU 93 discusses possible relations of ELLIS 88B bounds.

[30] KRAUSS 83 finds $m_{\widetilde{\gamma}}$ not 30 eV to 2.5 GeV. KRAUSS 83 takes into account the gravitino decay. Find that limits depend strongly on reheated temperature. For example a new allowed region $m_{\widetilde{\gamma}} = 4$–20 MeV exists if $m_{\text{gravitino}} < 40$ TeV. See figure 2.

$\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ (Neutralinos) MASS LIMITS

Neutralinos are unknown mixtures of photinos, z-inos, and neutral higgsinos (the supersymmetric partners of photons and of Z and Higgs bosons). The limits here apply only to $\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, and $\widetilde{\chi}^0_4$. $\widetilde{\chi}^0_1$ is the lightest supersymmetric particle (LSP); see $\widetilde{\chi}^0_1$ Mass Limits. It is not possible to quote rigorous mass limits because they are extremely model dependent; i.e. they depend on branching ratios of various $\widetilde{\chi}^0$ decay modes, on the masses of decay products ($\widetilde{e}$, $\widetilde{\gamma}$, $\widetilde{q}$, $\widetilde{g}$), and on the $\widetilde{e}$ mass exchanged in $e^+ e^- \rightarrow \widetilde{\chi}^0_i \widetilde{\chi}^0_j$. Often limits are given as contour plots in the $m_{\widetilde{\chi}^0} - m_{\widetilde{e}}$ plane vs other parameters. When specific assumptions are made, e.g, the neutralino is a pure photino ($\widetilde{\gamma}$), pure z-ino ($\widetilde{Z}$), or pure neutral higgsino ($\widetilde{H}^0$), the neutralinos will be labelled as such.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 45.3	95	[31] ACKERSTAFF 98L	OPAL	$\widetilde{\chi}^0_2$, $\tan\beta > 1$
> 75.8	95	[31] ACKERSTAFF 98L	OPAL	$\widetilde{\chi}^0_3$, $\tan\beta > 1$
>127	95	[32] ACCIARRI 95E	L3	$\widetilde{\chi}^0_4$, $\tan\beta > 3$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 92	95	[33] ACCIARRI 98F	L3	$\widetilde{H}^0_2$, $\tan\beta = 1.41$, $M_2 <$ 500 GeV
		[34] ABACHI 96	D0	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$
		[35] ABE 96K	CDF	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$
		[36] ACCIARRI 96F	L3	$\widetilde{\chi}^0_2$
> 86.3	95	[37] ACKERSTAFF 96C	OPAL	$\widetilde{\chi}^0_3$
> 45.3	95	[38] ALEXANDER 96J	OPAL	$\widetilde{\chi}^0_2 1.5 < \tan\beta < 35$
> 33.0	95	[39] ALEXANDER 96L	OPAL	$\widetilde{\chi}^0_2$, $\tan\beta > 1.5$
> 68	95	[40] BUSKULIC 96K	ALEP	$\widetilde{\chi}^0_2$
> 52	95	[32] ACCIARRI 95E	L3	$\widetilde{\chi}^0_2$, $\tan\beta > 3$
> 84	95	[32] ACCIARRI 95E	L3	$\widetilde{\chi}^0_3$, $\tan\beta > 3$
> 45	95	[41] DECAMP 92	ALEP	$\widetilde{\chi}^0_2$, $\tan\beta > 3$
		[42] ABREU 90G	DLPH	$Z \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$
		[43] AKRAWY 90N	OPAL	$Z \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$
> 57	90	[44] BAER 90	RVUE	$\widetilde{\chi}^0_3$; $\Gamma(Z)$; $\tan\beta > 1$
		[45] BARKLOW 90	MRK2	$Z \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$, $\widetilde{\chi}^0_2 \widetilde{\chi}^0_2$
		[46] DECAMP 90K	ALEP	$Z \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$
> 41	95	[47] SAKAI 90	AMY	$e^+ e^- \rightarrow \widetilde{H}^0_1 \widetilde{H}^0_2$ $(\widetilde{H}^0_2 \rightarrow f\overline{f}\widetilde{H}^0_1)$
> 31	95	[48] BEHREND 87B	CELL	$e^+ e^- \rightarrow \widetilde{\gamma}\widetilde{Z}$ $(\widetilde{Z} \rightarrow q\overline{q}\widetilde{\gamma})$, $m_{\widetilde{e}} <$ 70 GeV

> 30	95	[49] BEHREND	87B	CELL	$e^+e^- \to \tilde{\gamma}\tilde{Z}$ $(\tilde{Z} \to q\bar{q}\tilde{g})$
> 31.3	95	[50] BEHREND	87B	CELL	$e^+e^- \to \tilde{H}^0_1\tilde{H}^0_2$ $(\tilde{H}^0_2 \to f\bar{f}\tilde{H}^0_1)$
> 22	95	[51] BEHREND	87B	CELL	$e^+e^- \to \gamma\tilde{\gamma}\tilde{Z}$ $(\tilde{Z} \to \tilde{\nu}\nu)$
		[52] AKERLOF	85	HRS	$e^+e^- \to \tilde{\gamma}\tilde{\chi}^0$ $(\tilde{\chi}^0 \to q\bar{q}\tilde{\gamma})$
none 1–21	95	[53] BARTEL	85L	JADE	$e^+e^- \to \tilde{H}^0_1\tilde{H}^0_2$, $\tilde{H}^0_2 \to f\bar{f}\tilde{H}^0_1$
		[54] BEHREND	85	CELL	$e^+e^- \to$ monojet X
> 35	95	[55] ADEVA	84B	MRKJ	$e^+e^- \to \gamma\tilde{Z}$ $(\tilde{Z} \to \ell\bar{\ell}\tilde{\gamma})$
> 28	95	[56] BARTEL	84C	JADE	$e^+e^- \to \gamma\tilde{Z}$ $(\tilde{Z} \to f\bar{f}\tilde{\gamma})$
		[57] ELLIS	84	COSM	

[31] ACKERSTAFF 98L is obtained from direct searches in the $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_{2,3}$ production channels, and indirectly from $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ searches within the MSSM. See footnote to ACKERSTAFF 98L in the chargino Section for further details on the assumptions. Data taken at $\sqrt{s}$=130–172 GeV.

[32] ACCIARRI 95E limits go down to 0 GeV ($\tilde{\chi}^0_2$), 60 GeV ($\tilde{\chi}^0_3$), and 90 GeV ($\tilde{\chi}^0_4$) for tanβ=1.

[33] ACCIARRI 98F is obtained from direct searches in the $e^+e^- \to \tilde{\chi}^0_{1,2}\tilde{\chi}^0_2$ production channels, and indirectly from $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ searches within the MSSM. See footone to ACCIARRI 98F in the chargino Section for futher details on the assumptions. Data taken at $\sqrt{s}$ = 130–172 GeV.

[34] ABACHI 96 searches for 3-lepton final states. Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented as lower bounds on $\sigma(\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2) \times B(\tilde{\chi}^{\pm}_1 \to \ell\nu_\ell\tilde{\chi}^0_1) \times B(\tilde{\chi}^0_2 \to \ell^+\ell^-\tilde{\chi}^0_1)$ as a function of $m_{\tilde{\chi}^0_1}$. Limits range from 3.1 pb ($m_{\tilde{\chi}^0_1}$ = 45 GeV) to 0.6 pb ($m_{\tilde{\chi}^0_1}$ = 100 GeV).

[35] ABE 96K looked for tripleton events from chargino-neutralino production. They obtained lower bounds on $m_{\tilde{\chi}^0_2}$ as a function of μ. The lower bounds are in the 45–50 GeV range for gaugino-dominant $\tilde{\chi}^0_2$ with negative μ, if tanβ <10. See paper for more details of the assumptions.

[36] ACCIARRI 96F looked for associated production $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$. See the paper for upper bounds on the cross section. Data taken at $\sqrt{s}$ = 130–136 GeV.

[37] ACKERSTAFF 96C is obtained from direct searches in the $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_{2,3}$ production channel, and indirectly from $\tilde{\chi}^{\pm}_1$ searches within MSSM. Data from $\sqrt{s}$ = 130, 136, and 161 GeV are combined. The same assumptions and constraints of ALEXANDER 96J apply. The limit improves to 94.3 GeV for m_0 = 1 TeV.

[38] ALEXANDER 96J looked for associated $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$. A universal scalar mass m_0 at the grand unification scale is assumed. The bound is for the smallest possible value of m_0 alowed by the LEP $\tilde{\ell}$, $\tilde{\nu}$ mass limits, 1.5 <tanβ <35. Branching fractions are calculated using minimal supergravity. The bound is for $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ >10 GeV. The limit improves to 47.5 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136 GeV. ACKERSTAFF 96C, using data from $\sqrt{s}$ = 161 GeV, improves the limit for m_0 = 1 TeV to 51.9 GeV.

[39] ALEXANDER 96L bound for tanβ=35 is 51.5 GeV.

[40] BUSKULIC 96K looked for associated $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and assumed the dominance of off-shell Z-exchange in the $\tilde{\chi}^0_2$ decay. The bound is for $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ >9 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[41] For tanβ >2 the limit is >40 GeV; and it disappears for tanβ < 1.6.

[42] ABREU 90G exclude $B(Z \to \tilde{\chi}^0_1\tilde{\chi}^0_2) \geq 10^{-3}$ and $B(Z \to \tilde{\chi}^0_2\tilde{\chi}^0_2) \geq 2 \times 10^{-3}$ assuming $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 f\bar{f}$ via virtual Z. These exclude certain regions in model parameter space, see their Fig. 5.

[43] AKRAWY 90N exclude $B(Z \to \tilde{\chi}^0_1\tilde{\chi}^0_2) \gtrsim 3\text{–}5 \times 10^{-4}$ assuming $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 f\bar{f}$ or $\tilde{\chi}^0_1\gamma$ for most accessible masses. These exclude certain regions in model parameter space, see their Fig. 7.

[44] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by $\Delta\Gamma(Z) < 120$ MeV. These result from decays of Z to all combinations of $\tilde{\chi}^{\pm}_i$ and $\tilde{\chi}^0_i$. Minimal supersymmetry with tanβ > 1 is assumed.

[45] See Figs. 4, 5 in BARKLOW 90 for the excluded regions.

[46] DECAMP 90K exclude certain regions in model parameter space, see their figures.

[47] SAKAI 90 assume $m_{\tilde{H}^0_1} = 0$. The limit is for $m_{\tilde{H}^0_2}$.

[48] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to q\bar{q}\tilde{\gamma}) = 0.60$ and $B(\tilde{Z} \to e^+e^-\tilde{\gamma}) = 0.13$. $m_{\tilde{e}_L} = m_{\tilde{e}_R} < 70$ GeV. $m_{\tilde{\gamma}} < 10$ GeV.

[49] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to q\bar{q}\tilde{g}) = 1$. $m_{\tilde{e}_L} = m_{\tilde{e}_R} < 70$ GeV. $m_{\tilde{\gamma}} = 0$.

[50] Pure higgsino. The LSP is the other higgsino and is taken massless. Limit degraded if $\tilde{\chi}^0$ not pure higgsino or if LSP not massless.

[51] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to \tilde{\nu}\nu) = 1$. $m_{\tilde{e}_L} = m_{\tilde{e}_R} = 26$ GeV. $m_{\tilde{\gamma}} = 10$ GeV. No excluded region remains for $m_{\tilde{e}}$ >30 GeV.

[52] AKERLOF 85 is e^+e^- monojet search motivated by UA1 monojet events. Observed only one event consistent with $e^+e^- \to \tilde{\gamma}+\tilde{\chi}^0$ where $\tilde{\chi}^0 \to$ monojet. Assuming that missing-p_T is due to $\tilde{\gamma}$, and monojet due to $\tilde{\chi}^0$, limits dependent on the mixing and $m_{\tilde{e}}$ are given, see their figure 4.

[53] BARTEL 85L assume $m_{\tilde{H}^0_1} = 0$, $\Gamma(Z \to \tilde{H}^0_1\tilde{H}^0_2) \gtrsim \frac{1}{2}\Gamma(Z \to \nu_e\bar{\nu}_e)$. The limit is for $m_{\tilde{H}^0_2}$.

[54] BEHREND 85 find no monojet at E_{cm} = 40–46 GeV. Consider $\tilde{\chi}^0$ pair production via Z^0. One is assumed as massless and escapes detector. Limit is for the heavier one, decaying into a jet and massless $\tilde{\chi}^0$. Both $\tilde{\chi}^0$'s are assumed to be pure higgsino. For these very model-dependent results, BEHREND 85 excludes m = 1.5–19.5 GeV.

[55] ADEVA 84B observed no events with signature of acoplanar lepton pair with missing energy. Above example limit is for $m_{\tilde{\gamma}}$ <2 GeV and $m_{\tilde{e}}$ <40 GeV, and assumes $B(\tilde{Z} \to \mu^+\mu^-\tilde{\gamma}) = B(\tilde{Z} \to e^+e^-\tilde{\gamma}) = 0.10$. BR = 0.05 gives 33.5 GeV limit.

[56] BARTEL 84C search for $e^+e^- \to \tilde{Z}+\tilde{\gamma}$ with $\tilde{Z} \to \tilde{\gamma}+e^+e^-$, $\mu^+\mu^-$, $q\bar{q}$, etc. They see no acoplanar events with missing-p_T due to two $\tilde{\gamma}$'s. Above example limit is for $m_{\tilde{e}}$ = 40 GeV and for light stable $\tilde{\gamma}$ with $B(\tilde{Z} \to e^+e^-\tilde{\gamma}) = 0.1$.

[57] ELLIS 84 find if lightest neutralino is stable, then $m_{\tilde{\chi}^0}$ not 100 eV – 2 GeV (for $m_{\tilde{q}}$ = 40 GeV). The upper limit depends on $m_{\tilde{q}}$ (similar to the $\tilde{\gamma}$ limit) and on nature of $\tilde{\chi}^0$. For pure higgsino the higher limit is 5 GeV.

Unstable $\tilde{\chi}^0_1$ (Lightest Neutralino) MASS LIMIT

Unless stated otherwise, the limits below assume that the $\tilde{\gamma}$ decays either into $\gamma\tilde{G}$ (goldstino) or into $\gamma\tilde{H}^0$ (Higgsino).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>77	95	[58] ABBOTT	98	D0	$p\bar{p} \to \gamma\gamma \not{E}_T+X$
		[59] ABREU	98	DLPH	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ $(\tilde{\chi}^0_1 \to \gamma\tilde{G})$
		[60] ACKERSTAFF	98J	OPAL	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ $(\tilde{\chi}^0_1 \to \gamma\tilde{G})$
	95	[61] ACCIARRI	97V	L3	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ $(\tilde{\chi}^0_1 \to \gamma\tilde{G})$
		[62] ELLIS	97	THEO	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \to \gamma\tilde{G}$
		[63] BUSKULIC	96U	ALEP	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ $(\tilde{\chi}^0_1 \to \nu\ell\bar{\ell}')$
>40	95	[64] BUSKULIC	95E	ALEP	$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ $(\tilde{\chi}^0_1 \to \nu\ell\bar{\ell}')$
		[65] BUSKULIC	95E	ALEP	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ $(\tilde{\gamma} \to \nu\ell\bar{\ell}')$
		[66] ACTON	93G	OPAL	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ $(\tilde{\gamma} \to \tau^{\pm}\ell^{\mp}\nu_{\ell'})$
		[67] ABE	89J	VNS	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ $(\tilde{\gamma} \to \gamma\tilde{G}$ or $\gamma\tilde{H}^0)$
>15	95	[68] BEHREND	87B	CELL	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ $(\tilde{\gamma} \to \gamma\tilde{G}$ or $\gamma\tilde{H}^0)$
		[69] ADEVA	85	MRKJ	
		[70] BALL	84	CALO	Beam dump
		[71] BARTEL	84B	JADE	
		[71] BEHREND	83	CELL	
		[72] CABIBBO	81	COSM	

[58] ABBOTT 98 studied the chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\tilde{G}$. The limit assumes the gaugino mass unification.

[59] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. Upper bounds on $\gamma\gamma\not{E}$ cross section are obtained. Similar limits on $\gamma\not{E}$ are also given, relevant for $e^+e^- \to \tilde{\chi}^0_1\tilde{G}$ production.

[60] ACKERSTAFF 98J looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=161–172 GeV. They set limits on $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1)$ in the range 0.22–0.50 pb for $m_{\tilde{\chi}^0_1}$ in the range 45–86 GeV. Mass limits for explicit models from the literature are given in Fig. 19 of their paper. Similar limits on γ+missing energy are also given, relevant for $\tilde{\chi}^0_1\tilde{G}$ production.

[61] ACCIARRI 97V looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=161 and 172 GeV. They set limits on $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1)$ in the range 0.25–0.50 pb for masses in the range 45–85 GeV. The lower limits on $m_{\tilde{\chi}^0_1}$ vary in the range of 64.8 GeV (pure bino with 90 GeV slepton) to 75.3 GeV (pure higgsino). There is no limit for pure zino case.

[62] ELLIS 97 reanalyzed the LEP2 ($\sqrt{s}$=161 GeV) limits of $\sigma(\gamma\gamma+E_{\text{miss}})$< 0.2 pb to exclude $m_{\tilde{\chi}^0_1}$ < 63 GeV if $m_{\tilde{e}_L}$=$m_{\tilde{e}_R}$ < 150 GeV and $\tilde{\chi}^0_1$ decays to $\gamma\tilde{G}$ inside detector.

[63] BUSKULIC 96U extended the search for $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ in BUSKULIC 95E under the same assumptions. See their Fig. 5 for excluded region in the neutralino-chargino parameter space. Data taken at $\sqrt{s}$ = 130–136 GeV.

[64] BUSKULIC 95E looked for $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$, where $\tilde{\chi}^0_1$ decays via R-parity violating interaction into one neutrino and two opposite-charge leptons. The bound applies provided that $B(Z \to \tilde{\chi}^0_1\tilde{\chi}^0_1) > 3 \times 10^{-5}\beta^3$, β being the final state $\tilde{\chi}^0_1$ velocity.

[65] BUSKULIC 95E looked for $e^+e^- \to \tilde{\gamma}\tilde{\gamma}$, where $\tilde{\gamma}$ decays via R-parity violating interaction into one neutrino and two opposite-charge leptons. They extend the domain in the $(m_{\tilde{e}}, m_{\tilde{\gamma}})$ plane excluded by ACTON 93G to $m_{\tilde{e}}$ >220 GeV/c^2 (for $m_{\tilde{\gamma}}$=15 GeV/c^2) and to $m_{\tilde{\gamma}}$ >2 GeV/c^2 (for $m_{\tilde{e}}$ <220 GeV/c^2).

[66] ACTON 93G assume R-parity violation and decays $\tilde{\gamma} \to \tau^{\pm}\ell^{\mp}\nu_\ell$ (ℓ= e or μ). They exclude $m_{\tilde{\gamma}}$ = 4–43 GeV for $m_{\tilde{e}_L}$ <42 GeV, and $m_{\tilde{\gamma}}$ = 7–30 GeV for $m_{\tilde{e}_L}$ <100 GeV (95% CL). Assumes $\tilde{e}_R$ much heavier than $\tilde{e}_L$, and lepton family number violation but L_e-L_μ conservation.

[67] ABE 89J exclude $m_{\tilde{\gamma}}$ = 0.15–25 GeV (95%CL) for d = (100 GeV)^2 and $m_{\tilde{e}}$ = 40 GeV in the case $\tilde{\gamma} \to \gamma\tilde{G}$, and $m_{\tilde{\gamma}}$ up to 23 GeV for $m_{\tilde{e}}$ = 40 GeV in the case $\tilde{\gamma} \to \gamma\tilde{H}^0$.

[68] BEHREND 87B limit is for unstable photinos only. Assumes $B(\tilde{\gamma} \to \gamma(\tilde{G}$ or $\tilde{H}^0))$ =1, $m_{\tilde{G}\text{or}\tilde{H}^0} \ll m_{\tilde{\gamma}}$ and pure $\tilde{\gamma}$ eigenstate. $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ < 100 GeV.

[69] ADEVA 85 is sensitive to $\tilde{\gamma}$ decay path <5 cm. With $m_{\tilde{e}}$ = 50 GeV, limit (CL = 90%) is $m_{\tilde{\gamma}}$ >20.5 GeV. Assume $\tilde{\gamma}$ decays to photon + goldstino and search for acoplanar photons with large missing p_T.

[70] BALL 84 is FNAL beam dump experiment. Observed no $\tilde{\gamma}$ decay, where $\tilde{\gamma}$'s are expected to come from $\tilde{g}$'s produced at the target. Three possible $\tilde{\gamma}$ lifetimes are considered. Gluino decay to goldstino + gluon is also considered.

[71] BEHREND 83 and BARTEL 84B look for 2γ events from $\tilde{\gamma}$ pair production. With supersymmetric breaking parameter d = (100 GeV)^2 and $m_{\tilde{e}}$ = 40 GeV the excluded

regions at CL = 95% would be $m_{\tilde\gamma}$ = 100 MeV – 13 GeV for BEHREND 83 $m_{\tilde\gamma}$ = 80 MeV – 18 GeV for BARTEL 84B. Limit is also applicable if the $\tilde\gamma$ decays radiatively within the detector.

[72] CABIBBO 81 consider $\tilde\gamma \rightarrow \gamma +$ goldstino. Photino must be either light enough (<30 eV) to satisfy cosmology bound, or heavy enough (>0.3 MeV) to have disappeared at early universe.

$\tilde\chi_1^\pm$, $\tilde\chi_2^\pm$ (Charginos) MASS LIMITS

Charginos ($\tilde\chi^\pm$'s) are unknown mixtures of w-inos and charged higgsinos (the supersymmetric partners of W and Higgs bosons). Mass limits are relatively model dependent, so assumptions concerning branching ratios need to be specified. When specific assumptions are made, e.g. the chargino is a pure w-ino ($\widetilde{W}$) or pure charged higgsino ($\widetilde{H}^\pm$), the charginos will be labelled as such.

In the Listing below, we use $\Delta m_+ = m_{\tilde\chi_1^\pm} - m_{\tilde\chi_1^0}$ $\Delta m_\nu = m_{\tilde\chi_1^\pm} - m_{\tilde\nu}$, or simply Δm to indicate that the constraint applies to both Δm_+ and Δm_ν.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 67.6	95	[73] ABREU	98	DLPH	$\Delta m >$ 10 GeV
> 69.2	95	[74] ACCIARRI	98F	L3	$\tan\beta < 1.41$
> 65.7	95	[75] ACKERSTAFF	98L	OPAL	$\Delta m_+ >$ 3 GeV
> 56.3	95	[76] ABREU	96L	DLPH	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$
> 64	95	[77] ACCIARRI	96F	L3	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$, $m_{\tilde\chi^0} <$ 43 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>150	95	[78] ABBOTT	98	D0	$p\overline{p} \rightarrow \gamma\gamma \not{E}_T$+X
		[79] ABBOTT	98C	D0	$p\overline{p} \rightarrow \tilde\chi_1^\pm\tilde\chi_2^0$
> 71.8	95	[80] ABREU	98	DLPH	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$, $\tilde\chi_1^0 \rightarrow \tilde G\gamma$
		[81] ACKERSTAFF	98K	OPAL	$\tilde\chi^+ \rightarrow \ell^+ \not{E}$
		[82] CARENA	97	THEO	$g_\mu - 2$
		[83] KALINOWSKI	97	THEO	$W \rightarrow \tilde\chi_1^\pm\tilde\chi_1^0$
		[84] ABE	96K	CDF	$p\overline{p} \rightarrow \tilde\chi_1^\pm\tilde\chi_2^0$
> 62	95	[85] ACKERSTAFF	96C	OPAL	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$
> 58.7	95	[86] ALEXANDER	96J	OPAL	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$
> 63	95	[87] BUSKULIC	96K	ALEP	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$
		[88] BUSKULIC	96U	ALEP	$e^+e^- \rightarrow \tilde\chi_1^+\tilde\chi_1^-$; R-parity violation
> 44.0	95	[89] ADRIANI	93M	L3	$Z \rightarrow \tilde\chi^+\tilde\chi^-$, $\Gamma(Z)$
> 45.2	95	[90] DECAMP	92	ALEP	$Z \rightarrow \tilde\chi^+\tilde\chi^-$, all $m_{\tilde\chi_1^0}$
> 47	95	[90] DECAMP	92	ALEP	$Z \rightarrow \tilde\chi^+\tilde\chi^-$, $m_{\tilde\chi_1^0}$ <41 GeV
> 99	95	[91] HIDAKA	91	RVUE	$\tilde\chi_2^\pm$
> 44.5	95	[92] ABREU	90G	DLPH	$Z \rightarrow \tilde\chi^+\tilde\chi^-$, $m_{\tilde\gamma} <$ 20 GeV
> 45	95	[93] AKESSON	90B	UA2	$p\overline{p} \rightarrow ZX$ $(Z \rightarrow \widetilde{W}^+\widetilde{W}^-)$
> 45	95	[94] AKRAWY	90D	OPAL	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$; $m_{\tilde\gamma} <$ 20 GeV
> 45	95	[95] BARKLOW	90	MRK2	$Z \rightarrow \widetilde{W}^+\widetilde{W}^-$
> 42	95	[96] BARKLOW	90	MRK2	$Z \rightarrow \widetilde{H}^+\widetilde{H}^-$
> 44.5	95	[97] DECAMP	90C	ALEP	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$; $m_{\tilde\gamma} <$ 28 GeV
> 25.5	95	[98] ADACHI	89	TOPZ	$e^+e^- \rightarrow \tilde\chi^+\tilde\chi^-$
> 44	95	[99] ADEVA	89B	L3	$e^+e^- \rightarrow \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W} \rightarrow \ell\tilde\nu$ or $\ell\nu\tilde\gamma$
> 45	90	[100] ANSARI	87D	UA2	$p\overline{p} \rightarrow ZX$ $(Z \rightarrow \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W}^\pm \rightarrow e^\pm\tilde\nu)$

[73] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The universal scalar mass at the GUT scale is assumed to compute branching fractions and mass spectrum. The limit is for 41 $< m_{\tilde\nu} <$ 100 GeV, and $\tan\beta$=1–35. The limit improves to 84.3 GeV for $m_{\tilde\nu} >$ 300 GeV. For Δm_+ below 10 GeV, the limit is independent of $m_{\tilde\nu}$, and is given by 80.3 GeV for $\Delta m_+ =$ 5 GeV, and by 52.4 GeV for $\Delta m_+ =$ 3 GeV.

[74] ACCIARRI 98F evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The limit is obtained for $0 < M_2 < 2000$, $\tan\beta < 1.41$, and $\mu = -200$ GeV, and holds for all values of m_0. No dependence on the trilinear-coupling parameter A is found. It improves to 84 GeV for large sneutrino mass, at μ=−200 GeV. See the paper for limits obtained with specific assumptions on the gaugino/higgsino composition of the state. Data taken at $\sqrt{s}$ = 130–172 GeV.

[75] ACKERSTAFF 98L evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The limit is obtained for $0 < M_2 < 1500$, $|\mu| < 500$ and $\tan\beta > 1$, but remains valid outside this domain. The dependence on the trilinear-coupling parameter A is studied, and found neglibible. The limit holds for the smallest value of m_0 consistent with scalar lepton constraints (ACKERSTAFF 97H) and for all values of m_0 where the condition $\Delta m_{\tilde\nu} >$ 2.0 GeV is satisfied. $\Delta m_\nu >$ 10 GeV if $\tilde\chi^\pm \rightarrow \ell\tilde\nu_\ell$. The limit improves to 84.5 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$=130–172 GeV.

[76] ABREU 96L assumes the dominance of off-shell W-exchange in the chargino decay and $\Delta(m)$ >10 GeV. The bound is for the smallest $\tilde\ell$, $\tilde\nu$ mass allowed by LEP, provided either $m_{\tilde\nu} > m_{\tilde\chi^\pm}$ or $m_{\tilde\chi^\pm} - m_{\tilde\nu}$ >10 GeV. 1<$\tan\beta$ <35. For a mostly higgsino $\tilde\chi^+$ ($m_{\tilde\chi^\pm} - m_{\tilde\chi^0}$=5 GeV) the limit is 63.8 GeV, independently of the $\tilde\ell$ masses. Data taken at $\sqrt{s}$ = 130–136 GeV.

[77] ACCIARRI 96F assume $m_{\tilde\nu}$ >200 GeV and $m_{\tilde\chi_1^\pm} < m_{\tilde\chi_2^0}$. See their Fig. 4 for excluded regions in the ($m_{\tilde\chi^\pm}$,$m_{\tilde\chi^0}$) plane. Data taken at $\sqrt{s}$ = 130–136 GeV.

[78] ABBOTT 98 studied the chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\tilde G$. The limit assumes the gaugino mass unification.

[79] ABBOTT 98C searches for trilepton final states (ℓ=e,μ). Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented in Fig. 1 of their paper as lower bounds on $\sigma(p\overline{p} \rightarrow \tilde\chi^\pm\tilde\chi_2^0)\times$B($3\ell$). Limits range from 0.66 pb ($m_{\tilde\chi_1^\pm}$=45 GeV) to 0.10 pb ($m_{\tilde\chi_1^\pm}$=124 GeV).

[80] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The universal scalar mass at the GUT scale is assumed to compute branching fractions and mass spectrum, and the radiative decay of the lightest neutralino into gravitino is assumed. The limit is for $\Delta m >$ 10 GeV, 41 $< m_{\tilde\nu} <$ 100 GeV, and $\tan\beta$=1–35. The limit improves to 84.5 GeV if either $m_{\tilde\nu} >$ 300 GeV, or Δm_+=1 GeV independently of $m_{\tilde\nu}$.

[81] ACKERSTAFF 98K looked for dilepton+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. Limits on $\sigma(e^+e^- \rightarrow \tilde\chi_1^+\tilde\chi_1^-)\times$B$^2(\ell)$, with B($\ell$)=B($\chi^+ \rightarrow \ell^+\nu_\ell\chi_1^0$) (B($\ell$)=B($\chi^+ \rightarrow \ell^+\tilde\nu_\ell$)), are given in Fig. 16 (Fig. 17).

[82] CARENA 97 studied the constraints on chargino and sneutrino masses from muon $g-2$. The bound can be important for large $\tan\beta$.

[83] KALINOWSKI 97 studies the constraints on the chargino-neutralino parameter space from limits on $\Gamma(W \rightarrow \tilde\chi_1^\pm\tilde\chi_1^0)$ achievable at LEP2. This is relevant when $\tilde\chi_1^\pm$ is "invisible," i.e., if $\tilde\chi_1^\pm$ dominantly decays into $\tilde\nu_\ell\ell^\pm$ with little energy for the lepton. Small otherwise allowed regions could be excluded.

[84] ABE 96K looked for tripleton events from chargino-neutralino production. The bound on $m_{\tilde\chi_1^\pm}$ can reach up to 47 GeV for specific choices of parameters. The limits on the combined production cross section times 3-lepton branching ratios range between 1.4 and 0.4 pb, for 45<$m_{\tilde\chi_1^\pm}$(GeV)<100. See the paper for more details on the parameter dependence of the results.

[85] ACKERSTAFF 96C assumes the dominance of off-shell W-exchange in the chargino decay and applies for Δm>10 GeV in the region of parameter space defined by: M_2 <1500 GeV, $|\mu|$ <500 GeV and $\tan\beta > 1.5$. The bound is for the smallest $\tilde\ell$,$\tilde\nu$ mass allowed by LEP, with the efficiency for $\tilde\chi^\pm \rightarrow \tilde\nu\nu$ decays set to zero. The limit improves to 78.5 GeV for m_0 = 1 TeV. Data taken at $\sqrt{s}$ = 130,136, and 161 GeV.

[86] ALEXANDER 96J assumes a universal scalar mass m_0 at the grand unification scale. The bound is for the smallest possible value of m_0 alowed by the LEP $\tilde\ell$, $\tilde\nu$ mass limits. 1.5 <$\tan\beta$ <35. Branching fractions are calculated using minimal supergravity. The bound is for $\Delta(m)$ >10 GeV. The limit improves to 65.4 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[87] BUSKULIC 96K assumes the dominance of off-shell W-exchange in the chargino decay and applies throughout the (M_2,μ) plane for 1.41 <$\tan\beta$ <35 provided either $m_{\tilde\nu} > m_{\tilde\chi^\pm}$ and $m_{\tilde\chi^\pm} - m_{\tilde\chi_1^0}$ >4 GeV, or $m_{\tilde\chi^\pm} - m_{\tilde\nu}$ >4 GeV. The limit improves to 67.8 GeV for a pure gaugino $\tilde\chi^\pm$ and $m_{\tilde\nu}$ >200 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[88] BUSKULIC 96U searched for pair-produced charginos which decay into $\tilde\chi_1^0$ with either leptons or hadrons, where $\tilde\chi_1^0$ further decays leptonically via R-parity violating interactions. See their Fig. 5 for excluded region in the neutralino-chargino parameter space. Data taken at $\sqrt{s}$ = 130–136 GeV.

[89] ADRIANI 93M limit from $\Delta\Gamma(Z)$< 35.1 MeV. For pure wino, the limit is 45.5 GeV.

[90] DECAMP 92 limit is for a general $\tilde\chi^\pm$ (all contents).

[91] HIDAKA 91 limit obtained from LEP and preliminary CDF limits on the gluino mass (as analyzed in BAER 91).

[92] ABREU 90G limit is for a general $\tilde\chi^\pm$. They assume charginos have a three-body decay such as $\ell^+\nu\tilde\gamma$.

[93] AKESSON 90B assume $\widetilde{W} \rightarrow e\tilde\nu$ with B > 20% and $m_{\tilde\nu} = 0$. The limit disappears if $m_{\tilde\nu}$ > 30 GeV.

[94] AKRAWY 90D assume charginos have three-body decay such as $\ell^+\nu\tilde\gamma$ (i.e. $m_{\tilde\nu} > m_{\tilde\chi^+}$). A two-body decay, $\tilde\chi^+ \rightarrow \ell\tilde\nu$ would have been seen by their search for acoplanar leptons. The result is independent of the hadronic branching ratio. They search for acoplanar electromagnetic clusters and quark jets.

[95] BARKLOW 90 assume 100% $\widetilde{W} \rightarrow W^*\tilde\chi_1^0$. Valid up to $m_{\tilde\chi_1^0} \lesssim [m_{\widetilde{W}} - 5\text{ GeV}]$.

[96] BARKLOW 90 assume 100% $\widetilde{H} \rightarrow H^*\tilde\chi_1^0$. Valid up to $m_{\tilde\chi_1^0} \lesssim [m_{\widetilde{H}} - 8\text{ GeV}]$.

[97] DECAMP 90C assume charginos have three-body decay such as $\ell^+\nu\tilde\gamma$ (i.e. $m_{\tilde\nu} > m_{\tilde\chi^+}$), and branching ratio to each lepton is 11%. They search for acoplanar dimuons, dielectrons, and μe events. Limit valid for $m_{\tilde\gamma}$ < 28 GeV.

[98] ADACHI 89 assume only single photon annihilation in the production. The limit applies for arbitrary decay branching ratios with B($\tilde\chi \rightarrow e\nu\tilde\gamma$) + B($\tilde\chi \rightarrow \mu\nu\tilde\gamma$) + B($\tilde\chi \rightarrow \tau\nu\tilde\gamma$) + B($\tilde\chi \rightarrow q\overline{q}\tilde\gamma$) = 1 (lepton universality is *not* assumed). The limit is for $m_{\tilde\gamma}$ = 0 but a very similar limit is obtained for $m_{\tilde\gamma}$ = 10 GeV. For B($\tilde\chi \rightarrow q\overline{q}\tilde\gamma$) = 1, the limit increases to 27.8 GeV.

[99] ADEVA 89B assume for $\ell\nu\tilde\gamma$ ($\ell\tilde\nu$) mode that B(e) = B(μ) = B(τ) = 11% (33%) and search for acoplanar dimuons, dielectrons, and μe events. Also assume $m_{\tilde\gamma}$ < 20 GeV and for $\ell\tilde\nu$ mode that $m_{\tilde\nu}$ = 10 GeV.

[100] ANSARI 87D looks for high p_T e^+e^- pair with large missing p_T at the CERN $p\overline{p}$ collider at E_{cm} = 546–630 GeV. The limit is valid when $m_{\tilde\nu} \lesssim$ 20 GeV, B($\widetilde{W} \rightarrow e\tilde\nu_e$) = 1/3, and B($Z \rightarrow \widetilde{W}^+\widetilde{W}^-$) is calculated by assuming pure gaugino eigenstate. See their Fig. 3(b) for excluded region in the $m_{\widetilde{W}} - m_{\tilde\nu}$ plane.

Long-lived $\tilde{\chi}^{\pm}$ (Chargino) MASS LIMITS

Limits on charginos which leave the detector before decaying.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
>80	95	[101] ABREU	97D DLPH
>83	95	[102] BARATE	97K ALEP
>45	95	ABREU	90G DLPH
>28.2	95	ADACHI	90C TOPZ

[101] ABREU 97D bound applies only to masses above 45 GeV. Data collected in e^+e^- collisions at $\sqrt{s}$=130–172 GeV. The limit improves to 84 GeV for $m_{\tilde{\nu}} > 200$ GeV.

[102] BARATE 97K uses e^+e^- data collected at $\sqrt{s}$ = 130–172 GeV. Limit valid for $\tan\beta = \sqrt{2}$ and $m_{\tilde{\nu}} > 100$ GeV. The limit improves to 86 GeV for $m_{\tilde{\nu}} > 250$ GeV.

$\tilde{\nu}$ (Sneutrino) MASS LIMIT

The limit depends on the number, $N(\tilde{\nu})$, of sneutrinos assumed to be degenerate in mass. Only $\tilde{\nu}_L$ (not $\tilde{\nu}_R$) exist. It is possible that $\tilde{\nu}$ could be the lightest supersymmetric particle (LSP).

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 43.1	95	[103] ELLIS	96B RVUE	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=3
> 41.8	95	[104] ADRIANI	93M L3	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=3
> 37.1	95	[104] ADRIANI	93M L3	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=1
> 41	95	[105] DECAMP	92 ALEP	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=3
> 36	95	ABREU	91F DLPH	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=1
> 32	95	[106] ABREU	91F DLPH	$\Gamma(Z)$; $N(\tilde{\nu})$=1
> 31.2	95	[107] ALEXANDER	91F OPAL	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=1
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$\neq m_Z$	95	[108] ACCIARRI	97U L3	R-parity violation
none 125–180	95	[108] ACCIARRI	97U L3	R-parity violation
		[109] CARENA	97 THEO	$g_{\mu} - 2$
> 46.0	95	[110] BUSKULIC	95E ALEP	$N(\tilde{\nu})$=1, $\tilde{\nu} \rightarrow \nu\nu\ell\overline{\ell}'$
none 20–25000		[111] BECK	94 COSM	Stable $\tilde{\nu}$, dark matter
<600		[112] FALK	94 COSM	$\tilde{\nu}$ LSP, cosmic abundance
none 3–90	90	[113] SATO	91 KAMI	Stable $\tilde{\nu}_e$ or $\tilde{\nu}_{\mu}$, dark matter
none 4–90	90	[113] SATO	91 KAMI	Stable $\tilde{\nu}_{\tau}$, dark matter
> 31.4	95	[114] ADEVA	90I L3	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=1
> 39.4	95	[114] ADEVA	90I L3	$\Gamma(Z \rightarrow$ invisible); $N(\tilde{\nu})$=3

[103] ELLIS 96B uses combined LEP data available in the Summer 1995, which constrain the number of neutrino species to N_{ν}=2.991 ± 0.016.

[104] ADRIANI 93M limit from $\Delta\Gamma(Z)$(invisible)< 16.2 MeV.

[105] DECAMP 92 limit is from $\Gamma(\text{invisible})/\Gamma(\ell\ell) = 5.91 \pm 0.15$ ($N_{\nu} = 2.97 \pm 0.07$).

[106] ABREU 91F limit (>32 GeV) is independent of sneutrino decay mode.

[107] ALEXANDER 91F limit is for one species of $\tilde{\nu}$ and is derived from $\Gamma(\text{invisible, new})/\Gamma(\ell\ell) < 0.38$.

[108] ACCIARRI 97U studied the effect of the s-channel tau-sneutrino exchange in $e^+e^- \rightarrow e^+e^-$ at $\sqrt{s}=m_Z$ and $\sqrt{s}$=130–172 GeV, via the R-parity violating coupling $\lambda_{131}L_1L_I e_1$. The limits quoted here hold for $\lambda_{131} > 0.05$. Similar limits were studied in $e^+e^- \rightarrow \mu^+\mu^-$ together with $\lambda_{232}L_2L_3e_2$ coupling.

[109] CARENA 97 studied the constraints on chargino and sneutrino masses from muon $g-2$. The bound can be important for large $\tan\beta$.

[110] BUSKULIC 95E looked for $Z \rightarrow \tilde{\nu}\overline{\tilde{\nu}}$, where $\tilde{\nu} \rightarrow \nu\chi_1^0$ and χ_1^0 decays via R-parity violating interactions into two leptons and a neutrino.

[111] BECK 94 limit can be inferred from limit on Dirac neutrino using $\sigma(\tilde{\nu}) = 4\sigma(\nu)$. Also private communication with H.V. Klapdor-Kleingrothaus.

[112] FALK 94 puts an upper bound on $m_{\tilde{\nu}}$ when $\tilde{\nu}$ is LSP by requiring its relic density does not overclose the Universe.

[113] SATO 91 search for high-energy neutrinos from the sun produced by annihilation of sneutrinos in the sun. Sneutrinos are assumed to be stable and to constitute dark matter in our galaxy. SATO 91 follow the analysis of NG 87, OLIVE 88, and GAISSER 86.

[114] ADEVA 90I limit is from $\Delta N_{\nu} < 0.19$.

$\tilde{e}$ (Selectron) MASS LIMIT

Limits assume $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ unless otherwise stated. When the assumption of a universal scalar mass parameter m_0 for $\tilde{e}_L$ and $\tilde{e}_R$ is mentioned, the relation between $m_{\tilde{e}_R}$ and $m_{\tilde{e}_L}$ can be found in the "Note on Supersymmetry."

In the Listings below, we use $\Delta m = m_{\tilde{e}} - m_{\tilde{\chi}_1^0}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 56	95	[115] ACCIARRI	98F L3	$\Delta m>$ 5 GeV, $\tilde{e}_R^+\tilde{e}_R^-$, $\tan\beta \geq 1.41$
> 58.0	95	[116] ACKERSTAFF	98K OPAL	$\Delta(m) >$ 5 GeV, $\tilde{e}_R^+\tilde{e}_R^-$
> 55	95	[117] ACKERSTAFF	97H OPAL	$\Delta(m) >$ 5 GeV, $\tilde{e}_R^+\tilde{e}_R^-$
> 58	95	[118] BARATE	97N ALEP	$\Delta(m) >$ 3 GeV, $\tilde{e}_R^+\tilde{e}_R^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 35	95	[119] BARATE	97N RVUE	$\tilde{e}_R$, $\Gamma^{\text{inv}}(Z)$
> 57	95	[120] ABREU	96O DLPH	$\Delta(m)$ >5 GeV, $\tilde{e}^+\tilde{e}^-$
> 50	95	[121] ACCIARRI	96F L3	$\Delta(m)$ >5 GeV, $\tilde{e}^+\tilde{e}^-$
> 63	95	[122] AID	96C H1	$m_{\tilde{q}}=m_{\tilde{e}}$, $m_{\tilde{\chi}_1^0}$=35 GeV
> 50	95	[123] BUSKULIC	96K ALEP	$\Delta(m)$ >10 GeV, $\tilde{e}_R^+\tilde{e}_R^-$, $\lvert\mu\rvert$= 1 TeV
> 63	90	[124] SUGIMOTO	96 AMY	$m_{\tilde{\gamma}}$ <5 GeV, $\gamma\tilde{\gamma}\tilde{\gamma}$
> 77	90	[125] SUGIMOTO	96 RVUE	$m_{\tilde{\gamma}}$ <5 GeV, $\gamma\tilde{\gamma}\tilde{\gamma}$
> 46	90	[126] ABE	95A TOPZ	$m_{\tilde{\gamma}}$ <5 GeV, $\gamma\tilde{\gamma}\tilde{\gamma}$
> 45.6	95	[127] BUSKULIC	95E ALEP	$\tilde{e} \rightarrow e\nu\ell\overline{\ell}'$
> 51.9	90	HOSODA	94 VNS	$m_{\tilde{\gamma}}$=0; $\gamma\tilde{\gamma}\tilde{\gamma}$
> 45	95	[128] ADRIANI	93M L3	$\Delta(m)$ >5 GeV, $\tilde{e}_R^+\tilde{e}_R^-$
> 45	95	[129] DECAMP	92 ALEP	$\Delta(m)$ >4 GeV, $\tilde{e}_R^+\tilde{e}_R^-$
> 42	95	ABREU	90G DLPH	$m_{\tilde{\gamma}}$ < 40 GeV; $\tilde{e}^+\tilde{e}^-$
> 38	95	[130] AKESSON	90B UA2	$m_{\tilde{\gamma}}$ = 0; $p\overline{p} \rightarrow ZX$ ($Z \rightarrow \tilde{e}^+\tilde{e}^-$)
> 43.4	95	[131] AKRAWY	90D OPAL	$m_{\tilde{\gamma}}$ < 30 GeV; $\tilde{e}^+\tilde{e}^-$
> 38.1	90	[132] BAER	90 RVUE	$\tilde{e}_L$; $\Gamma(Z)$; $\tan\beta$ > 1
> 43.5	95	[133] DECAMP	90C ALEP	$m_{\tilde{\gamma}}$ < 36 GeV; $\tilde{e}^+\tilde{e}^-$
>830		GRIFOLS	90 ASTR	$m_{\tilde{\gamma}}$ < 1 MeV
> 29.9	95	SAKAI	90 AMY	$m_{\tilde{\gamma}}$ < 20 GeV; $\tilde{e}^+\tilde{e}^-$
> 29	95	TAKETANI	90 VNS	$m_{\tilde{\gamma}}$ < 25 GeV; $\tilde{e}^+\tilde{e}^-$
> 60		[134] ZHUKOVSKII	90 ASTR	$m_{\tilde{\gamma}}$ = 0
> 28	95	[135] ADACHI	89 TOPZ	$m_{\tilde{\gamma}} \lesssim 0.85 m_{\tilde{e}}$; $\tilde{e}^+\tilde{e}^-$
> 41	95	[136] ADEVA	89B L3	$m_{\tilde{\gamma}}$ < 20 GeV; $\tilde{e}^+\tilde{e}^-$
> 32	90	[137] ALBAJAR	89 UA1	$p\overline{p} \rightarrow W^{\pm}X$ ($W^{\pm} \rightarrow \tilde{e}_L\tilde{\nu}$) ($\tilde{e}_L \rightarrow e\tilde{\gamma}$)
> 14	90	[138] ALBAJAR	89 UA1	$Z \rightarrow \tilde{e}^+\tilde{e}^-$
> 53	95	[139,140] HEARTY	89 ASP	$m_{\tilde{\gamma}}$=0; $\gamma\tilde{\gamma}\tilde{\gamma}$
> 50	95	HEARTY	89 ASP	$m_{\tilde{\gamma}}$ <5 GeV; $\gamma\tilde{\gamma}\tilde{\gamma}$
> 35	95	HEARTY	89 ASP	$m_{\tilde{\gamma}}$ <10 GeV; $\gamma\tilde{\gamma}\tilde{\gamma}$
> 51.5	90	[141,142] BEHREND	88B CELL	$m_{\tilde{\gamma}}$ = 0 GeV; $\gamma\tilde{\gamma}\tilde{\gamma}$
> 48	90	BEHREND	88B CELL	$m_{\tilde{\gamma}}$ < 5 GeV; $\gamma\tilde{\gamma}\tilde{\gamma}$

[115] ACCIARRI 98F looked for acoplanar dielectron+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes μ=−200 GeV, and zero efficiecny for decays other than $\tilde{e}_R \rightarrow e\tilde{\chi}_1^0$. See their Fig. 6 for the dependence of the limit on Δm.

[116] ACKERSTAFF 98K looked for dielectron+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes $\mu < -100$ GeV, $\tan\beta$=35, and zero efficiency for decays other than $\tilde{e}_R \rightarrow e\tilde{\chi}_1^0$. The limit improves to 66.5 GeV for $\tan\beta$=1.5.

[117] ACKERSTAFF 97H searched for acoplanar e^+e^-, assuming the MSSM with universal scalar mass and $\tan\beta$=1.5 but conservatively did not take the possible $\tilde{e}_L$ production into account. The limit improves to 68 GeV for the lightest allowed $\tilde{\chi}_1^0$, while it disappears for $\Delta(m) < 3$ GeV. The study includes data from e^+e^- collisions at $\sqrt{s}$=161 GeV, as well as 130–136 GeV (ALEXANDER 97B).

[118] BARATE 97N uses e^+e^- data collected at $\sqrt{s}$=161 and 172 GeV. The limit is for $\tan\beta$=2. It improves to 75 GeV if $\Delta(m)$ >35 GeV.

[119] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_{ν}=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[120] ABREU 96O bound assumes $\lvert\mu\rvert$ >200 GeV. The limit on $m_{\tilde{e}_R}$ obtained by assuming a heavy $\tilde{e}_L$ reduces to below 48 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[121] ACCIARRI 96F searched for acoplanar electron pairs. The limit is on $m_{\tilde{e}_R}$, under the assumption of a universal scalar mass in the range 0<m<100 GeV. It assumes 0<M<200 GeV, $-200 < \mu <0$ GeV, $\tan\beta$ = 1.5. The corresponding limit for for $m_{\tilde{e}_L}$ is 64 GeV. The bound on $m_{\tilde{e}_R}$ ($m_{\tilde{e}_L}$) improves to 58 GeV (70 GeV) for $m_{\tilde{\chi}_1^0}$=0. Data taken at $\sqrt{s}$ = 130–136 GeV.

[122] AID 96C used electron+jet events with missing energy and momentum to look for $eq \rightarrow \tilde{e}\tilde{q}$ via neutralino exchange with decays into $(e\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$. See the paper for dependences on $m_{\tilde{q}}$, $m_{\tilde{\chi}_1^0}$.

[123] BUSKULIC 96K searched for acoplanar electron pairs. The bound disappears for $\Delta(m)$ <10 GeV, while it improves to 59 GeV for $m_{\tilde{\chi}_1^0}$=0. If μ is small and the LSP higgsino-dominated, no bound beyond $m_Z/2$ exists. Data taken at $\sqrt{s}$ = 130–136 GeV.

[124] SUGIMOTO 96 looked for single photon production from e^+e^- annihilation at $\sqrt{s}$= 57.8 GeV. The lower bound improves to 65.5 GeV for a massless photino.

[125] SUGIMOTO 96 combined FORD 86, BEHREND 88B, HEARTY 89, HOSODA 94, ABE 95A, and SUGIMOTO 96 results. The lower bound improves to 79.3 GeV for a massless photino.

[126] ABE 95A looked for single photon production from e^+e^- annihilation at $\sqrt{s}$= 58 GeV. The lower bound improves to 47.2 GeV for a massless photino.

[127] BUSKULIC 95E looked for $Z \rightarrow \tilde{e}_R^+\tilde{e}_R^-$ where $\tilde{e}_R \rightarrow e\chi_1^0$ and χ_1^0 decays via R-parity violating interactions into two leptons and a neutrino.

[128] ADRIANI 93M used acolinear di-lepton events.

[129] DECAMP 92 limit improves for equal masses. They looked for acoplanar electrons.

[130] AKESSON 90B assume $m_{\tilde{\gamma}} = 0$. Very similar limits hold for $m_{\tilde{\gamma}} \lesssim 20$ GeV.

[131] AKRAWY 90D look for acoplanar electrons. For $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$, limit is 41.5 GeV, for $m_{\tilde{\gamma}} < 30$ GeV.

[132] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[133] DECAMP 90C look for acoplanar electrons. For $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$ limit is 42 GeV, for $m_{\tilde{\gamma}} < 33$ GeV.

[134] ZHUKOVSKII 90 set limit by saying the luminosity of a magnetized neutron star due to massless photino emission by electrons be small compared with its neutrino luminosity.

[135] ADACHI 89 assume only photon and photino exchange and $m_{\tilde{e}_L} = m_{\tilde{e}_R}$. The limit for the nondegenerate case is 26 GeV.

[136] ADEVA 89B look for acoplanar electrons.

[137] ALBAJAR 89 limit applies for $\tilde{e}_L$ when $m_{\tilde{e}_L} = m_{\tilde{\nu}_L}$ and $m_{\tilde{\gamma}} = 0$. See their Fig. 55 for the 90% CL excluded region in the $m_{\tilde{e}_L} - m_{\tilde{\nu}_L}$ plane. For $m_{\tilde{\nu}} = m_{\tilde{\gamma}} = 0$, limit is 50 GeV.

[138] ALBAJAR 89 assume $m_{\tilde{\gamma}} = 0$.

[139] HEARTY 89 assume $m_{\tilde{\gamma}} = 0$. The limit is very sensitive to $m_{\tilde{\gamma}}$; no limit can be placed for $m_{\tilde{\gamma}} \gtrsim 13$ GeV.

[140] The limit is reduced to 43 GeV if only one $\tilde{e}$ state is produced ($\tilde{e}_L$ or $\tilde{e}_R$ very heavy).

[141] BEHREND 88B limits assume pure photino eigenstate and $m_{\tilde{e}_L} = m_{\tilde{e}_R}$.

[142] The 95% CL limit for BEHREND 88B is 47.5 GeV for $m_{\tilde{\gamma}} = 0$. The limit for $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$ is 40 GeV at 90% CL.

$\tilde{\mu}$ (Smuon) MASS LIMIT

Limits assume $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$ unless otherwise stated.

In the Listings below, we use $\Delta(m)=m_{\tilde{\mu}} - m_{\tilde{\chi}^0_1}$. When limits on $m_{\tilde{\mu}_R}$ are quoted, it is understood that limits on $m_{\tilde{\mu}_L}$ are usually at least as strong.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>55	95	[143] ACCIARRI	98F	L3	$\Delta m > 5$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
>55.6	95	[144] ACKERSTAFF	98K	OPAL	$\Delta(m) > 4$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
>59	95	[145] BARATE	97N	ALEP	$\Delta(m) > 10$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>51	95	[146] ACKERSTAFF	97H	OPAL	$\Delta(m) > 5$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
>35	95	[147] BARATE	97N	RVUE	$\tilde{\mu}_R$, $\Gamma^{\text{inv}}(Z)$
>51	95	[148] ABREU	96O	DLPH	$\Delta(m) > 5$ GeV, $\tilde{\mu}^+ \tilde{\mu}^-$
>45.6	95	[149] BUSKULIC	95E	ALEP	$\tilde{\mu} \rightarrow \mu \nu \ell \overline{\ell}'$
>45	95	ADRIANI	93M	L3	$m_{\tilde{\chi}^0_1} < 40$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
>45	95	DECAMP	92	ALEP	$m_{\tilde{\chi}^0_1} < 41$ GeV, $\tilde{\mu}^+_R \tilde{\mu}^-_R$
>36	95	ABREU	90G	DLPH	$m_{\tilde{\gamma}} < 33$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$
>43	95	[150] AKRAWY	90D	OPAL	$m_{\tilde{\gamma}} < 30$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$
>38.1	90	[151] BAER	90	RVUE	$\tilde{\mu}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>42.6	95	[152] DECAMP	90C	ALEP	$m_{\tilde{\gamma}} < 34$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$
>27	95	SAKAI	90	AMY	$m_{\tilde{\gamma}} < 18$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$
>24.5	95	TAKETANI	90	VNS	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$
>24.5	95	[153] ADACHI	89	TOPZ	$m_{\tilde{\gamma}} \lesssim 0.8 m_{\tilde{\mu}}$; $\tilde{\mu}^+ \tilde{\mu}^-$
>41	95	[154] ADEVA	89B	L3	$m_{\tilde{\gamma}} < 20$ GeV; $\tilde{\mu}^+ \tilde{\mu}^-$

[143] ACCIARRI 98F looked for dimuon+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes $\mu=-200$ GeV, and zero efficiecny for decays other than $\tilde{\mu}_R \rightarrow \mu \tilde{\chi}^0_1$. See their Fig. 6 for the dependence of the limit on Δm.

[144] ACKERSTAFF 98K looked for dimuon+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes $\mu < -100$ GeV, $\tan\beta$=1.5, and zero efficiency for decays other than $\tilde{\mu}_R \rightarrow \mu \tilde{\chi}^0_1$. The limit improves to 62.7 GeV for $B(\tilde{\mu}_R \rightarrow \mu \tilde{\chi}^0_1)$=1.

[145] BARATE 97N uses $e^+ e^-$ data collected at $\sqrt{s}$=161 and 172 GeV. The limit assumes $B(\tilde{\mu} \rightarrow \mu \tilde{\chi}^0_1) = 1$.

[146] ACKERSTAFF 97H limit is for $m_{\tilde{\chi}^0_1} > 12$ GeV allowed by their chargino, neutralino search, and for $\tan\beta \geq 1.5$ and $|\mu| > 200$ GeV. The study includes data from $e^+ e^-$ collisions at $\sqrt{s}$=161 GeV, as well as at 130–136 GeV (ALEXANDER 97B).

[147] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_ν=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[148] Data taken at $\sqrt{s}$ = 130–136 GeV.

[149] BUSKULIC 95E looked for $Z \rightarrow \tilde{\mu}^+_R \tilde{\mu}^-_R$, where $\tilde{\mu}_R \rightarrow \mu \chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[150] AKRAWY 90D look for acoplanar muons. For $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$, limit is 41.0 GeV, for $m_{\tilde{\gamma}} < 30$ GeV.

[151] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) $<$ 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[152] DECAMP 90C look for acoplanar muons. For $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$ limit is 40 GeV, for $m_{\tilde{\gamma}} <$ 30 GeV.

[153] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$ assumed. The limit for nondegenerate case is 22 GeV.

[154] ADEVA 89B look for acoplanar muons.

$\tilde{\tau}$ (Stau) MASS LIMIT

Limits assume $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$ unless otherwise stated.

In the Listings below, we use $\Delta(m)=m_{\tilde{\tau}} - m_{\tilde{\chi}^0_1}$. The limits depend on the potentially large mixing angle of the lightest mass eigenstate $\tilde{\tau}_1 = \tilde{\tau}_R \sin\theta_\tau + \tilde{\tau}_L \sin\theta_\tau$. The coupling to the Z vanishes for $\theta_\tau = 0.82$.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>53	95	[155] BARATE	97N	ALEP	$\Delta(m) > 30$ GeV, $\theta_\tau=\pi/2$
>47	95	[155] BARATE	97N	ALEP	$\Delta(m) > 30$ GeV, $\theta_\tau=0.82$
>35	95	[156] BARATE	97N	RVUE	$\tilde{\tau}_R$, $\Gamma^{\text{inv}}(Z)$
>44	95	[157] ADRIANI	93M	L3	$m_{\tilde{\chi}^0_1} < 38$ GeV, $\tilde{\tau}^+ \tilde{\tau}^-$
>45	95	[158] DECAMP	92	ALEP	$m_{\tilde{\chi}^0_1} < 38$ GeV, $\tilde{\tau}^+ \tilde{\tau}^-$
>43.0	95	[159] AKRAWY	90D	OPAL	$m_{\tilde{\gamma}} < 23$ GeV; $\tilde{\tau}^+ \tilde{\tau}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45.6	95	[160] BUSKULIC	95E	ALEP	$\tilde{\tau} \rightarrow \tau \nu \ell \overline{\ell}'$
>35	95	ABREU	90G	DLPH	$m_{\tilde{\gamma}} < 25$ GeV; $\tilde{\tau}^+ \tilde{\tau}^-$
>38.1	90	[161] BAER	90	RVUE	$\tilde{\tau}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>40.4	95	[162] DECAMP	90C	ALEP	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\tau}^+ \tilde{\tau}^-$
>25	95	SAKAI	90	AMY	$m_{\tilde{\gamma}} < 10$ GeV; $\tilde{\tau}^+ \tilde{\tau}^-$
>25.5	95	TAKETANI	90	VNS	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\tau}^+ \tilde{\tau}^-$
>21.7	95	[163] ADACHI	89	TOPZ	$m_{\tilde{\gamma}}$=0; $\tilde{\tau}^+ \tilde{\tau}^-$

[155] BARATE 97N uses $e^+ e^-$ data collected at $\sqrt{s}$=161 and 172 GeV.

[156] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_ν=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[157] ADRIANI 93M limit is for $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$.

[158] DECAMP 92 limit is for $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$; for equal masses the limit would improve. They looked for acoplanar particles.

[159] AKRAWY 90D look for acoplanar particles. For $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$, limit is 41.0 GeV, for $m_{\tilde{\gamma}} < 23$ GeV.

[160] BUSKULIC 95E looked for $Z \rightarrow \tilde{\tau}^+_R \tilde{\tau}^-_R$, where $\tilde{\tau}_R \rightarrow \tau \chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[161] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) $<$ 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[162] DECAMP 90C look for acoplanar charged particle pairs. Limit is for $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$. For $m_{\tilde{\gamma}} \leq 24$ GeV, the limit is 37 GeV. For $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$ and $m_{\tilde{\gamma}} < 15$ GeV, the limit is 33 GeV.

[163] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$ assumed.

Stable $\tilde{\ell}$ (Slepton) MASS LIMIT

Limits on scalar leptons which leave detector before decaying. Limits from Z decays are independent of lepton flavor. Limits from continuum $e^+ e^-$ annihilation are also independent of flavor for smuons and staus. However, selectron limits from continuum $e^+ e^-$ annihilation depend on flavor because there is an additional contribution from neutralino exchange that in general yields stronger limits. All limits assume $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R}$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>65	95	[164] ABREU	97D	DLPH	$\tilde{\mu}_r$ or $\tilde{\tau}_R$
>67	95	[165] BARATE	97K	ALEP	$\tilde{\mu}_R$, $\tilde{\tau}_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>40	95	ABREU	90G	DLPH	
>26.3	95	ADACHI	90C	TOPZ	$\tilde{\mu}$, $\tilde{\tau}$
>38.8	95	AKRAWY	90O	OPAL	$\tilde{\ell}_R$
>27.1	95	[166] SAKAI	90	AMY	
>32.6	95	SODERSTROM	90	MRK2	
>24.5	95	[167] ADACHI	89	TOPZ	

[164] ABREU 97D bound applies only to masses above 45 GeV. The mass limit improves to 68 GeV for $\tilde{\mu}_L$, $\tilde{\tau}_L$. Data collected in $e^+ e^-$ collisions at $\sqrt{s}$=130–172 GeV.

[165] BARATE 97K uses $e^+ e^-$ data collected at $\sqrt{s}$ = 130–172 GeV. The mass limit improves to 69 GeV for $\tilde{\mu}_L$ and $\tilde{\tau}_L$.

[166] SAKAI 90 limit improves to 30.1 GeV for $\tilde{e}$ if $m_{\tilde{\gamma}} \approx m_{\tilde{e}}$.

[167] ADACHI 89 assume only photon (and photino for $\tilde{e}$) exchange. The limit for $\tilde{e}$ improves to 26 GeV for $m_{\tilde{\gamma}} \approx m_{\tilde{e}}$.

$\tilde{q}$ (Squark) MASS LIMIT

For $m_{\tilde{q}} > 60$–70 GeV, it is expected that squarks would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included. The limits from Z decay do not assume GUT relations and are more model independent.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 224	95	[168] ABE	96D	CDF	$m_{\tilde{g}} \leq m_{\tilde{q}}$; with cascade decays
> 176	95	[169] ABACHI	95C	D0	Any $m_{\tilde{g}} < 300$ GeV; with cascade decays
> 212	95	[169] ABACHI	95C	D0	$m_{\tilde{g}} \leq m_{\tilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[170] DATTA	97	THEO	$\tilde{\nu}$'s lighter than $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$
> 216	95	[171] DERRICK	97	ZEUS	$ep \rightarrow \tilde{q}$, $\tilde{q} \rightarrow \mu J$ or τJ, R-parity violation
none 130–573	95	[172] HEWETT	97	THEO	$q\tilde{g} \rightarrow \tilde{q}$, $\tilde{q} \rightarrow q\tilde{g}$, with a light gluino
none 190–650	95	[173] TEREKHOV	97	THEO	$qg \rightarrow \tilde{q}\tilde{g}$, $\tilde{q} \rightarrow q\tilde{g}$, with a light gluino
> 215	95	[174] AID	96	H1	$ep \rightarrow \tilde{q}$, R-parity violation, λ=0.3
> 150	95	[174] AID	96	H1	$ep \rightarrow \tilde{q}$, R-parity violation, λ=0.1
> 63	95	[175] AID	96C	H1	$m_{\tilde{q}}=m_{\tilde{e}}$, $m_{\tilde{\chi}^0_1}$=35 GeV

none 330–400	95	[176] TEREKHOV	96	THEO	$ug \to \tilde{u}\tilde{g}$, $\tilde{u} \to u\tilde{g}$ with a light gluino
		[177] ABE	95T	CDF	$\tilde{q} \to \tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$
> 45.3	95	[178] BUSKULIC	95E	ALEP	$\tilde{q} \to q\nu\ell\overline{\ell}'$
> 239	95	[179] AHMED	94B	H1	$ep \to \tilde{q}$; R-parity violation, λ=0.30
> 135	95	[179] AHMED	94B	H1	$ep \to \tilde{q}$; R-parity violation, λ=0.1
> 35.3	95	[180] ADRIANI	93M	L3	$Z \to \tilde{u}\overline{\tilde{u}}$, $\Gamma(Z)$
> 36.8	95	[180] ADRIANI	93M	L3	$Z \to \tilde{d}\overline{\tilde{d}}$, $\Gamma(Z)$
> 90	90	[181] ABE	92L	CDF	Any $m_{\tilde{g}}$ <410 GeV; with cascade decay
> 218	90	[182] ABE	92L	CDF	$m_{\tilde{g}} = m_{\tilde{q}}$; with cascade decay
> 180	90	[181] ABE	92L	CDF	$m_{\tilde{g}} < m_{\tilde{q}}$; with cascade decay
> 100		[183] ROY	92	RVUE	$p\overline{p} \to \tilde{q}\tilde{q}$; R-parity violating
		[184] NOJIRI	91	COSM	
> 45	95	[185] ABREU	90F	DLPH	$Z \to \tilde{q}\overline{\tilde{q}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 43	95	[186] ABREU	90F	DLPH	$Z \to \tilde{d}\overline{\tilde{d}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 42	95	[187] ABREU	90F	DLPH	$Z \to \tilde{u}\overline{\tilde{u}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 27.0	95	ADACHI	90C	TOPZ	Stable $\tilde{u}$, $\tilde{u}\overline{\tilde{u}}$
> 74	90	[188] ALITTI	90	UA2	Any $m_{\tilde{q}}$; $B(\tilde{q} \to q\tilde{g}$ or $q\tilde{\gamma}) = 1$
> 106	90	[188] ALITTI	90	UA2	$m_{\tilde{q}} = m_{\tilde{g}}$; $B(\tilde{q} \to q\tilde{\gamma}) = 1$
> 39.2	90	[189] BAER	90	RVUE	$\tilde{d}_L$; $\Gamma(Z)$
> 45	95	[190,191] BARKLOW	90	MRK2	$Z \to \tilde{q}\overline{\tilde{q}}$
> 40	95	[190,192] BARKLOW	90	MRK2	$Z \to \tilde{d}\overline{\tilde{d}}$
> 39	95	[190,193] BARKLOW	90	MRK2	$Z \to \tilde{u}\overline{\tilde{u}}$
>1100		GRIFOLS	90	ASTR	$m_{\tilde{\gamma}} < 1$ MeV
> 24	95	SAKAI	90	AMY	$e^+e^- \to \tilde{d}\overline{\tilde{d}} \to d\overline{d}\tilde{\gamma}\tilde{\gamma}$; $m_{\tilde{\gamma}} < 10$ GeV
> 26	95	SAKAI	90	AMY	$e^+e^- \to \tilde{u}\overline{\tilde{u}} \to u\overline{u}\tilde{\gamma}\tilde{\gamma}$; $m_{\tilde{\gamma}} < 10$ GeV
> 26.3	95	[194] ADACHI	89	TOPZ	$e^+e^- \to \tilde{q}\overline{\tilde{q}} \to q\overline{q}\tilde{\gamma}\tilde{\gamma}$
		[195] NATH	88	THEO	$\tau(p \to \nu K)$ in supergravity GUT
> 45	90	[196] ALBAJAR	87D	UA1	Any $m_{\tilde{g}} > m_{\tilde{q}}$
> 75	90	[196] ALBAJAR	87D	UA1	$m_{\tilde{g}} = m_{\tilde{q}}$

[168] ABE 96D searched for production of gluinos and five degenerate squarks in final states containing a pair of leptons, two jets, and missing E_T. The two leptons arise from the semileptonic decays of charginos produced in the cascade decays. The limit is derived for fixed $\tan\beta = 4.0$, $\mu = -400$ GeV, and $m_{H^+} = 500$ GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario.

[169] ABACHI 95C assume five degenerate squark flavors with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed $\tan\beta = 2.0$ $\mu = -250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space. No limit is given for m_{gluino} >547 GeV.

[170] DATTA 97 argues that the squark mass bound by ABACHI 95C can be weakened by 10–20 GeV if one relaxes the assumption of the universal scalar mass at the GUT-scale so that the $\tilde{\chi}^{\pm}_1$,$\tilde{\chi}^0_2$ in the squark cascade decays have dominant and invisible decays to $\tilde{\nu}$.

[171] DERRICK 97 looked for lepton-number violating final states via R-parity violating couplings $\lambda'_{ijk}L_iQ_jd_k$. When $\lambda'_{11k}\lambda'_{ijk} \neq 0$, the process $eu \to \tilde{d}^*_k \to \ell_i u_j$ is possible. When $\lambda'_{1j1}\lambda'_{ijk} \neq 0$, the process $e\overline{d} \to \tilde{u}^*_j \to \ell_i\overline{d}_k$ is possible. 100% branching fraction $\tilde{q} \to \ell j$ is assumed. The limit quoted here corresponds to $\tilde{t} \to \tau q$ decay, with λ'=0.3. For different channels, limits are slightly better. See Table 6 in their paper.

[172] HEWETT 97 reanalyzed the limits on possilbe resonances in di-jet mode ($\tilde{q} \to q\tilde{g}$) from ALITTI 93 quoted in "Limits for Excited q (q^*) from Single Production," ABE 96 in "SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$," and unpublished CDF, D0 bounds. The bound applies to the gluino mass of 5 GeV, and improves for lighter gluino. The analysis has gluinos in parton distribution function.

[173] TEREKHOV 97 improved the analysis of TEREKHOV 96 by including di-jet angular distributions in the analysis.

[174] AID 96 looked for first-generation squarks as s-channel resonances singly produced in ep collision via the R-parity violating coupling in the superpotential $W=\lambda L_1 Q_1 d_1$. The degeneracy of squarks $\tilde{Q}_1$ and $\tilde{d}_1$ is assumed. Eight different channels of possible squark decays are considered.

[175] AID 96C used electron+jet events with missing energy and momentum to look for $eq \to \tilde{e}\tilde{q}$ via neutralino exchange with decays into $(e\tilde{\chi}^0_1)(q\tilde{\chi}^0_1)$. See the paper for dependences on $m_{\tilde{e}}$, $m_{\tilde{\chi}^0_1}$.

[176] TEREKHOV 96 reanalyzed the limits on possible resonances in di-jet mode ($\tilde{u} \to u\tilde{g}$) from ABE 95N quoted in "MASS LIMITS for g_A (axigluon)." The bound applies only to the case with a light gluino.

[177] ABE 95T looked for a cascade decay of five degenerate squarks into $\tilde{\chi}^0_2$ which further decays into $\tilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu = -40$ GeV, $\tan\beta = 1.5$, and heavy gluinos, the range $50 < m_{\tilde{q}}$ (GeV)<110 is excluded at 90% CL. See the paper for details.

[178] BUSKULIC 95E looked for $Z \to \tilde{q}\overline{\tilde{q}}$, where $\tilde{q} \to q\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[179] AHMED 94B looked for squarks as s-channel resonance in ep collision via R-parity violating coupling in the superpotential $W = \lambda L_1 Q_1 d_1$. The degeneracy of all squarks Q_1 and d_1 is assumed. The squarks decay dominantly via the same R-violating coupling into eq or νq if $\lambda \gtrsim 0.2$. For smaller λ, decay into photino is assumed which subsequently decays into $eq\overline{q}$, and the bound depends on $m_{\tilde{\gamma}}$. See paper for excluded region on $(m_{\tilde{q}},\lambda)$ plane.

[180] ADRIANI 93M limit from $\Delta\Gamma(Z) < 35.1$ MeV and assumes $m_{\tilde{q}_L} \gg m_{\tilde{q}_R}$.

[181] ABE 92L assume five degenerate squark flavors and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. ABE 92L includes the effect of cascade decay, for a particular choice of parameters, $\mu = -250$ GeV, $\tan\beta = 2$. Results are weakly sensitive to these parameters over much of parameter space. No limit for $m_{\tilde{q}} \leq 50$ GeV (but other experiments rule out that region). Limits are 10–20 GeV higher if $B(\tilde{q} \to q\tilde{\gamma}) = 1$. Limit assumes GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\tilde{\chi}^0_1} \approx m_{\tilde{g}}/6$. This last relation implies that as $m_{\tilde{g}}$ increases, the mass of $\tilde{\chi}^0_1$ will eventually exceed $m_{\tilde{q}}$ so that no decay is possible. Even before that occurs, the signal will disappear; in particular no bounds can be obtained for $m_{\tilde{g}}$ >410 GeV. m_{H^+}=500 GeV.

[182] ABE 92L bounds are based on similar assumptions as ABACHI 95C. No limits for m_{gluino} >410 GeV.

[183] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on squark production in R-parity violating models. The 100% decay $\tilde{q} \to q\tilde{\chi}$ where $\tilde{\chi}$ is the LSP, and the LSP decays either into $\ell q\overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[184] NOJIRI 91 argues that a heavy squark should be nearly degenerate with the gluino in minimal supergravity not to overclose the universe.

[185] ABREU 90F assume six degenerate squarks and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. $m_{\tilde{q}} < 41$ GeV is excluded at 95% CL for $m_{\text{LSP}} < m_{\tilde{q}} - 2$ GeV.

[186] ABREU 90F exclude $m_{\tilde{d}} < 38$ GeV at 95% for $m_{\text{LSP}} < m_{\tilde{d}} - 2$ GeV.

[187] ABREU 90F exclude $m_{\tilde{u}} < 36$ GeV at 95% for $m_{\text{LSP}} < m_{\tilde{u}} - 2$ GeV.

[188] ALITTI 90 searched for events having $\geq$ 2 jets with $E^1_T > 25$ GeV, $E^2_T > 15$ GeV, $|\eta| < 0.85$, and $\Delta\phi < 160^\circ$, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{q} \to q\tilde{\gamma}$ (if $m_{\tilde{q}} < m_{\tilde{g}}$) or $\tilde{q} \to q\tilde{g}$ (if $m_{\tilde{q}} > m_{\tilde{g}}$) decay and $m_{\tilde{\gamma}} \lesssim$ 20 GeV. Five degenerate squark flavors and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$ are assumed. Masses below 50 GeV are not excluded by the analysis.

[189] BAER 90 limit from $\Delta\Gamma(Z) < 120$ MeV, assuming $m_{\tilde{d}_L} = m_{\tilde{u}_L} = m_{\tilde{e}_L} = m_{\tilde{\nu}}$. Independent of decay modes. Minimal supergravity assumed.

[190] BARKLOW 90 assume 100% $\tilde{q} \to q\tilde{\gamma}$.

[191] BARKLOW 90 assume five degenerate squarks (left- and right-handed). Valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{q}} - 4\text{ GeV}]$.

[192] BARKLOW 90 result valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{d}} - 5\text{ GeV}]$.

[193] BARKLOW 90 result valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{u}} - 6\text{ GeV}]$.

[194] ADACHI 89 assume only photon exchange, which gives a a conservative limit. The limit is only for one flavor of charge 2/3 $\tilde{q}$. $m_{\tilde{q}_L} = m_{\tilde{q}_R}$ and $m_{\tilde{\gamma}} = 0$ assumed. The limit decreases to 26.1 GeV for $m_{\tilde{\gamma}} = 15$ GeV. The limit for nondegenerate case is 24.4 GeV.

[195] NATH 88 uses Kamioka limit of $\tau(p \to \overline{\nu}K^+) > 7 \times 10^{31}$ yrs to constrain squark mass $m_{\tilde{q}} > 1000$ GeV by assuming that the proton decay proceeds via an exchange of a color-triplet Higgsino of mass $< 10^{16}$ GeV in the supersymmetric SU(5) GUT. The limit applies for $m_{\tilde{\gamma}} \equiv (8/3)\sin^2\theta_W\tilde{m}_2 > 10$ GeV ($\tilde{m}_2$ is the SU(2) gaugino mass) and for a very conservative value of the three-quark proton wave function, barring cancellation between second and third generations. Lower squark mass is allowed if $m_{\tilde{\gamma}}$ as defined above is smaller.

[196] The limits of ALBAJAR 87D are from $p\overline{p} \to \tilde{q}\overline{\tilde{q}}X$ ($\tilde{q} \to q\tilde{\gamma}$) and assume 5 flavors of degenerate mass squarks each with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. They also assume $m_{\tilde{g}} > m_{\tilde{q}}$. These limits apply for $m_{\tilde{\gamma}} \lesssim 20$ GeV.

$\tilde{b}$ (Sbottom) MASS LIMIT

Limits in e^+e^- depend on the mixing angle of the mass eigenstate $\tilde{b}_1 = \tilde{b}_L\cos\theta_b + \tilde{b}_R\sin\theta_b$. Coupling to the Z vanishes for $\theta_b \sim 1.17$. In the Listings below, we use $\Delta m = m_{\tilde{b}_1} - m_{\tilde{\chi}^0_1}$.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>69.7	95	[197] ACKERSTAFF	97Q	OPAL	$\tilde{b} \to b\tilde{\chi}^0_1$, θ_b=0, $\Delta(m) > 8$ GeV
>73	95	[198] BARATE	97Q	ALEP	$\tilde{b} \to b\tilde{\chi}^0_1$, θ_b=0, $\Delta(m) > 10$ GeV
>53	95	[199] ABREU	96O	DLPH	$\tilde{b} \to b\tilde{\chi}^0$, θ_b=0, $\Delta(m)$ >20 GeV
>61.8	95	[200] ACKERSTAFF	96	OPAL	$\tilde{b} \to b\tilde{\chi}^0$, θ_b=0, $\Delta(m)$ >8 GeV

[197] ACKERSTAFF 97Q data taken at $\sqrt{s}$=130–172 GeV. See paper for dependence on θ_b. No limit for $\theta_b \approx 1.17$.

[198] BARATE 97Q uses data at $\sqrt{s}$=161, 170, and 172 GeV. The limit disappears when $\theta_b \approx 1.17$.

[199] Data taken at $\sqrt{s}$ = 130–136 GeV.

[200] ACKERSTAFF 96 also studied θ_b dependence when there is a mixing $\tilde{b}_1 = \tilde{b}_L \cos\theta_b + \tilde{b}_R \sin\theta_b$. Data taken at $\sqrt{s}$ = 130, 136, and 161 GeV. See the paper for dependence on θ_b. No limit for $\theta_b \approx 1.17$.

$\tilde{t}$ (Stop) MASS LIMIT

Limit depends on decay mode. In e^+e^- collisions they also depend on the mixing angle of the mass eigenstate $\tilde{t}_1 = \tilde{t}_L \cos\theta_t + \tilde{t}_R \sin\theta_t$. Coupling to Z vanishes when $\theta_t = 0.98$. In the Listings below, we use $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$ or $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\nu}}$, depending on relevant decay mode. See also bounds in "$\tilde{q}$ (Squark) MASS LIMIT."

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
> 73.3	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m) > 10$ GeV
> 65.0	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m) >$ 10 GeV
> 67.9	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to b\ell\tilde{\nu}$, θ_t=0, $\Delta(m) > 10$ GeV
> 56.2	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to b\ell\tilde{\nu}$, θ_t=0.98, $\Delta(m) >$ 10 GeV
> 66.3	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to b\tau\tilde{\nu}_\tau$, θ_t=0, $\Delta(m) > 10$ GeV
> 54.4	95	[201] ACKERSTAFF 97Q	OPAL	$\tilde{t} \to b\tau\tilde{\nu}_\tau$, θ_t=0.98, $\Delta(m) >$ 10 GeV
> 67	95	[202] BARATE 97Q	ALEP	$\tilde{t} \to c\tilde{\chi}^0_1$, any θ_t, $\Delta(m) > 10$ GeV
> 70	95	[202] BARATE 97Q	ALEP	$\tilde{t} \to b\ell\tilde{\nu}$, any θ_t, $\Delta(m) > 10$ GeV
> 64	95	[202] BARATE 97Q	ALEP	$\tilde{t} \to b\tau\tilde{\nu}_\tau$, any θ_t, $\Delta(m) >$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 61–91	95	[203] ABACHI 96B	D0	$\tilde{t} \to c\tilde{\chi}^0_1$, $m_{\tilde{\chi}^0_1}$ <30 GeV
> 54	95	[204] ABREU 96O	DLPH	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >5 GeV
> 52	95	[204] ACCIARRI 96F	L3	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >8 GeV
> 65.4	95	[205] ACKERSTAFF 96	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >10 GeV
> 56.8	95	[205] ACKERSTAFF 96	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >10 GeV
> 60.6	95	[205] ACKERSTAFF 96	OPAL	$\tilde{t} \to b\ell\tilde{\nu}$, θ_t=0, $\Delta(m)$ >10 GeV
none 9–24.4	95	[206] AID 96	H1	$ep \to \tilde{t}\tilde{t}$, R-parity violating decays
>138	95	[207] AID 96	H1	$ep \to \tilde{t}$, R-parity violation, $\lambda\cos\theta_t > 0.03$
> 48	95	[204] BUSKULIC 96K	ALEP	$t \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >18 GeV
> 57	95	[204] BUSKULIC 96K	ALEP	$t \to c\tilde{\chi}^0_1$, θ_t=π/2, $\Delta(m)$ >14 GeV
> 45		[208] CHO 96	RVUE	B^0-$\overline{B}^0$ and ϵ, θ_t= 0.98, $\tan\beta$ <2
none 11–41	95	[209] BUSKULIC 95E	ALEP	θ_t=0.98, $\tilde{t} \to c\nu\ell\overline{\ell}'$
none 6.0–41.2	95	AKERS 94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >2 GeV
none 5.0–46.0	95	AKERS 94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >5 GeV
none 11.2–25.5	95	AKERS 94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >2 GeV
none 7.9–41.2	95	AKERS 94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >5 GeV
none 7.6–28.0	95	[210] SHIRAI 94	VNS	$\tilde{t} \to c\tilde{\chi}^0_1$, any θ_t, $\Delta(m)$ >10 GeV
none 10–20	95	[210] SHIRAI 94	VNS	$\tilde{t} \to c\tilde{\chi}^0_1$, any θ_t, $\Delta(m) > 2.5$ GeV

[201] ACKERSTAFF 97Q looked for $\tilde{t}$ pair production. Data taken at $\sqrt{s}$=130, 136, 161, 170, and 172 GeV. Unless the ℓ=τ decay mode is explicitly indicated, the same branching fractions to ℓ=e, μ, and τ are assumed for $b\ell\tilde{\nu}_\ell$ modes. See Table 7 and Figs. 8–10 for other choices of θ_t, $\Delta(m)$, and leptonic branching ratios.

[202] BARATE 97Q uses e^+e^- data at $\sqrt{s}$=161, 170, and 172 GeV. Unless the ℓ=τ decay mode is explicitly indicated, the same branching fractions to ℓ=e, μ, and τ are assumed for $b\ell\tilde{\nu}_\ell$ modes. See their Figs. 4 and 5 for other choices of θ_t, $\Delta(m)$, and leptonic branching ratios.

[203] ABACHI 96B searches for final states with 2 jets and missing E_T. Limits on $m_{\tilde{t}}$ are given as a function of $m_{\tilde{\chi}^0_1}$. See Fig. 4 for details.

[204] Data taken at $\sqrt{s}$ = 130–136 GeV.

[205] ACKERSTAFF 96 looked for $\tilde{t}$ pair production. See the paper for θ_t and $\Delta(m)$ dependece of the limits. Data taken at $\sqrt{s}$ = 130, 136, and 161 GeV.

[206] AID 96 considers photoproduction of $\tilde{t}\tilde{t}$ pairs, with 100% R-parity violating decays of $\tilde{t}$ to eq, with q=d, s, or b quarks.

[207] AID 96 considers production and decay of $\tilde{t}$ via the R-parity violating coupling in the superpotential W=$\lambda L_1 Q_3 d_1$.

[208] CHO 96 studied the consistency among the B^0-$\overline{B}^0$ mixing, ϵ in K^0-$\overline{K}^0$ mixing, and the measurements of V_{cb}, V_{ub}/V_{cb}. For the range 25.5 GeV<$m_{\tilde{t}_1}$ <m_Z/2 left by AKERS 94K for θ_t = 0.98, and within the allowed range in M_2-μ parameter space from chargino, neutralino searches by ACCIARRI 95E, they found the scalar top contribution to B^0-$\overline{B}^0$ mixing and ϵ to be too large if $\tan\beta$ <2. For more on their assumptions, see the paper and their reference 10.

[209] BUSKULIC 95E looked for $Z \to \tilde{t}\overline{\tilde{t}}$, where $\tilde{t} \to c\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[210] SHIRAI 94 bound assumes the cross section without the s-channel Z-exchange and the QCD correction, underestimating the cross section up to 20% and 30%, respectively. They assume m_c=1.5 GeV.

Heavy $\tilde{g}$ (Gluino) MASS LIMIT

For $m_{\tilde{g}}$ > 60–70 GeV, it is expected that gluinos would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>173	95	[211] ABE 97K	CDF	Any $m_{\tilde{q}}$; with cascade decays
>216	95	[211] ABE 97K	CDF	$m_{\tilde{q}}$=$m_{\tilde{g}}$; with cascade decays
>224	95	[212] ABE 96D	CDF	$m_{\tilde{q}} = m_{\tilde{g}}$; with cascade decays
>154	95	[212] ABE 96D	CDF	$m_{\tilde{g}} < m_{\tilde{q}}$; with cascade decays
>212	95	[213] ABACHI 95C	D0	$m_{\tilde{g}} \geq m_{\tilde{q}}$; with cascade decays
>144	95	[213] ABACHI 95C	D0	Any $m_{\tilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[214] ABE 95T	CDF	$\tilde{g} \to \tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$
		[215] HEBBEKER 93	RVUE	e^+e^- jet analyses
>218	90	[216] ABE 92L	CDF	$m_{\tilde{q}} \leq m_{\tilde{g}}$; with cascade decay
>100	90	[216] ABE 92L	CDF	Any $m_{\tilde{q}}$; with cascade decay
>100		[217] ROY 92	RVUE	$p\overline{p} \to \tilde{g}\tilde{g}$; R-parity violating
>132	90	[218] HIDAKA 91	RVUE	
		[219] NOJIRI 91	COSM	
> 79	90	[220] ALITTI 90	UA2	Any $m_{\tilde{g}}$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$) = 1
>106	90	[220] ALITTI 90	UA2	$m_{\tilde{q}} = m_{\tilde{g}}$; B($\tilde{g} \to q\overline{q}\tilde{\gamma}$) = 1
		[221] NAKAMURA 89	SPEC	R-Δ^{++}
none 4–53	90	[222] ALBAJAR 87D	UA1	Any $m_{\tilde{q}} > m_{\tilde{g}}$
none 4–75	90	[222] ALBAJAR 87D	UA1	$m_{\tilde{q}} = m_{\tilde{g}}$
none 16–58	90	[223] ANSARI 87D	UA2	$m_{\tilde{q}} \lesssim 100$ GeV

[211] ABE 97K searched for production of gluinos and five degenerate squarks in events with three or more jets but no electrons or muons and missing transverse energy $\not{E}_T > 60$ GeV. The limit for any $m_{\tilde{q}}$ is for μ=$-$200 GeV and $\tan\beta$=2, and that for $m_{\tilde{q}}$=$m_{\tilde{g}}$ is for μ=$-$400 GeV and $\tan\beta$=4. Different choices for $\tan\beta$ and μ lead to changes of the order of $\pm$10 GeV in the limits. See Footnote [16] of the paper for more details on the assumptions.

[212] ABE 96D searched for production of gluinos and five degenerate squarks in final states containing a pair of leptons, two jets, and missing E_T. The two leptons arise from the semileptonic decays of charginos produced in the cascade decays. The limits are derived for fixed $\tan\beta = 4.0$, $\mu = -400$ GeV, and m_{H^+} = 500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the values of the three fixed parameters for a large fraction of parameter space. See Fig. 2 for the limits corresponding to different parameter choices.

[213] ABACHI 95C assume five degenerate squark flavors with with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed $\tan\beta = 2.0$ $\mu = -250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space.

[214] ABE 95T looked for a cascade decay of gluino into $\tilde{\chi}^0_2$ which further decays into $\tilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu = -40$ GeV, $\tan\beta = 1.5$, and heavy squarks, the range 50<$m_{\tilde{g}}$ (GeV)<140 is excluded at 90% CL. See the paper for details.

[215] HEBBEKER 93 combined jet analyses at various e^+e^- colliders. The 4-jet analyses at TRISTAN/LEP and the measured α_s at PEP/PETRA/TRISTAN/LEP are used. A constraint on effective number of quarks N=6.3 ± 1.1 is obtained, which is compared to that with a light gluino, N=8.

[216] ABE 92L bounds are based on similar assumptions as ABACHI 95C. Not sensitive to m_{gluino} <40 GeV (but other experiments rule out that region).

[217] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on gluino production in R-parity violating models. The 100% decay $\tilde{g} \to q\overline{q}\tilde{\chi}$ where $\tilde{\chi}$ is the LSP, and the LSP decays either into $\ell q\overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[218] HIDAKA 91 limit obtained from LEP and preliminary CDF results within minimal supersymmetry with gaugino-mass unification condition. HIDAKA 91 limit extracted from BAER 91 analysis.

[219] NOJIRI 91 argues that a heavy gluino should be nearly degenerate with squarks in minimal supergravity not to overclose the universe.

[220] ALITTI 90 searched for events having $\geq$ 2 jets with E^1_T > 25 GeV, E^2_T > 15 GeV, $|\eta|$ < 0.85, and $\Delta\phi$ < 160°, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{g} \to q\overline{q}\tilde{\gamma}$ decay and $m_{\tilde{\gamma}} \lesssim 20$ GeV. Masses below 50 GeV are not excluded by the analysis.

[221] NAKAMURA 89 searched for a long-lived ($\tau \gtrsim 10^{-7}$ s) charge-($\pm$2) particle with mass $\lesssim$ 1.6 GeV in proton-Pt interactions at 12 GeV and found that the yield is less than 10^{-8} times that of the pion. This excludes R-Δ^{++} (a $\tilde{g}uuu$ state) lighter than 1.6 GeV.

[222] The limits of ALBAJAR 87D are from $p\overline{p} \to \tilde{g}\tilde{g}X$ ($\tilde{g} \to q\overline{q}\tilde{\gamma}$) and assume $m_{\tilde{q}} > m_{\tilde{g}}$. These limits apply for $m_{\tilde{\gamma}} \lesssim 20$ GeV and $\tau(\tilde{g}) < 10^{-10}$ s.

[223] The limit of ANSARI 87D assumes $m_{\tilde{q}} > m_{\tilde{g}}$ and $m_{\tilde{\gamma}} \approx 0$.

NOTE ON LIGHT GLUINO

Written March 1998 by H. Murayama (UC Berkeley).

It is controversial if a light gluino of mass below 5 GeV is phenomenologically allowed. Below we list some of the most important and least controversial constraints which need to be met for a light gluino to be viable. For reviews on the subject, see, *e.g.*, Ref. 1.

1. Either $m_{\tilde{g}} \lesssim 1.5$ GeV or $m_{\tilde{g}} \gtrsim 3.5$ GeV to avoid the CAKIR 94 limit. See also Ref. 2 for similar quarkonium constraints on lighter masses.
2. The lifetime of the gluino or the ground state gluino-containing hadron (typically, $g\tilde{g}$) must be $\gtrsim 10^{-10}$ s in order to evade beam-dump and missing energy limits [1,2].
3. Charged gluino-containing hadrons (*e.g.* $\tilde{g}u\bar{d}$) must decay into neutral ones (*e.g.* $R^0(\tilde{g}g)\pi^+$ or $(\tilde{g}u\bar{u})e^-\bar{\nu}_e$) with a lifetime shorter than about 10^{-7} s to avoid the AKERS 95R limit. Older limits for lower masses and shorter lifetimes are summarized in Ref. 1.
4. The lifetime of $R^0 \rightarrow \rho^0\tilde{\gamma}$, if allowed, must be outside the ADAMS 97B range. The $R_p^+(\tilde{g}uud)$ state, which is believed to decay weakly into $S^0(\tilde{g}uds)\pi^\pm$ (FARRAR 96), must be heavier than 2 GeV or have lifetime $\tau_{R_p} \gtrsim 1$ ns or $\tau_{R_p} \lesssim 50$ ps (*e.g.* if the strong decay into $S^0K^\pm$ is allowed), or its production cross sections must be at least a factor of 5 smaller than those of hyperons, to avoid ALBUQUERQUE 97 limit.
5. $m_{\tilde{g}} \geq 6.8$ GeV (95% CL) if the "experimental optimization" method of fixing the renormalization scale is valid and if the hadronization and resummation uncertainties are as estimated in BARATE 97L, from the D_2 event shape observable in Z^0 decay. The 4-jet angular distribution is less sensitive to renormalization scale ambiguities and yields a 90%CL exclusion of a light gluino (DEGOUVEA 97). A combined LEP analysis based on all the Z^0 data and using the recent NLO calculations [3] is warranted.
6. Constraints from the effect of light gluinos on the running of α_s apply independently of the gluino lifetime and are insensitive to renormalization scale. They disfavor a light gluino at 70% CL (CSIKOR 97), which improves to more than 99% with jet analysis.

References

1. G.R. Farrar, Phys. Rev. **D51**, 3904 (1995); in SUSY 97, Proceedings of the Fifth International Conference on Supersymmetries in Physics," 27-31 May 1997, Philadelphia, USA, edited by M. Cvetic and P. Langacker (Nuc. Phys. B (Proc. Suppl.) 62 (1998)) p. 485. hep-ph/9710277.
2. R.M. Barnett, in SUSY 95, Proceedings of the International Workshop on Supersymmetry and Unification of Fundamental Interactions, Palaiseau, France, 15-19 May 1995, edited by I. Antoniadis and H. Videau (Editions Frontieres, Gif-sur-Yvette, France, 1996) p. 69.
3. L. Dixon and A. Signer, Phys. Rev. **D56**, 4031 (1997); J.M. Campbell, E.W.N. Glover, and D.J. Miller, Phys. Lett. **B409**, 503 (1997).

Long-lived/light $\tilde{g}$ (Gluino) MASS LIMIT

Limits on light gluinos ($m_{\tilde{g}}$ < 5 GeV), or gluinos which leave the detector before decaying.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[224] ADAMS 97B	KTEV	$pN \rightarrow R^0 \rightarrow \rho^0\tilde{\gamma}$
		[225] ALBUQUERQ...97	E761	$R^+(uud\tilde{g}) \rightarrow S^0(uds\tilde{g})\pi^+$, $X^-(ssd\tilde{g}) \rightarrow S^0\pi^-$
>6.3	95	[226] BARATE 97L	ALEP	Color factors
>5	99	[227] CSIKOR 97	RVUE	β function, $Z \rightarrow$ jets
>1.5	90	[228] DEGOUVEA 97	THEO	$Z \rightarrow jjjj$
		[229] FARRAR 96	RVUE	$R^0 \rightarrow \pi^0\tilde{\gamma}$
none 1.9–13.6	95	[230] AKERS 95R	OPAL	Z decay into a long-lived $(\tilde{g}q\bar{q})^\pm$
<0.7		[231] CLAVELLI 95	RVUE	quarkonia
none 1.5–3.5		[232] CAKIR 94	RVUE	$\Upsilon(1S) \rightarrow \gamma +$ gluinonium
not 3–5		[233] LOPEZ 93C	RVUE	LEP
≈ 4		[234] CLAVELLI 92	RVUE	α_s running
		[235] ANTONIADIS 91	RVUE	α_s running
>1		[236] ANTONIADIS 91	RVUE	$pN \rightarrow$ missing energy
>3.8	90	[237] ARNOLD 87	EMUL	π^- (350 GeV). $\sigma \simeq A^1$
>3.2	90	[237] ARNOLD 87	EMUL	π^- (350 GeV). $\sigma \simeq A^{0.72}$
none 0.6–2.2	90	[238] TUTS 87	CUSB	$\Upsilon(1S) \rightarrow \gamma +$ gluinonium
none 1 –4.5	90	[239] ALBRECHT 86C	ARG	$1 \times 10^{-11} \lesssim \tau \lesssim 1 \times 10^{-9}$s
none 1–4	90	[240] BADIER 86	BDMP	$1 \times 10^{-10} < \tau < 1 \times 10^{-7}$s
none 3–5		[241] BARNETT 86	RVUE	$p\bar{p} \rightarrow$ gluino gluino gluon
none		[242] VOLOSHIN 86	RVUE	If (quasi) stable; $\tilde{g}uud$
none 0.5–2		[243] COOPER-... 85B	BDMP	For $m_{\tilde{q}}$=300 GeV
none 0.5–4		[243] COOPER-... 85B	BDMP	For $m_{\tilde{q}}$ <65 GeV
none 0.5–3		[243] COOPER-... 85B	BDMP	For $m_{\tilde{q}}$=150 GeV
none 2–4		[244] DAWSON 85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5		[244] DAWSON 85	RVUE	For $m_{\tilde{q}}$=100 GeV
none 0.5–4.1	90	[245] FARRAR 85	RVUE	FNAL beam dump
>1		[246] GOLDMAN 85	RVUE	Gluononium
>1–2		[247] HABER 85	RVUE	
		[248] BALL 84	CALO	
		[249] BRICK 84	RVUE	
		[250] FARRAR 84	RVUE	
>2		[251] BERGSMA 83C	RVUE	For $m_{\tilde{q}}$ <100 GeV
		[252] CHANOWITZ 83	RVUE	$\tilde{g}u\bar{d}$, $\tilde{g}uud$
>2–3		[253] KANE 82	RVUE	Beam dump
>1.5–2		FARRAR 78	RVUE	R-hadron

[224] ADAMS 97B looked for $\rho^0 \rightarrow \pi^+\pi^-$ as a signature of R^0=$(\tilde{g}g)$ bound states. The experiment is sensitive to an R^0 mass range of 1.2–4.5 GeV and to a lifetime range of 10^{-10}–10^{-3} sec. Precise limits depend on the assumed value of $m_{R^0}/m_{\tilde{\gamma}}$. See Fig. 7 for the excluded mass and lifetime region.

[225] ALBUQUERQUE 97 looked for weakly decaying baryon-like states which contain a light gluino, following the suggestions in FARRAR 96. See their Table 1 for limits on the production fraction. These limits exclude gluino masses in the range 100–600 MeV for the predicted lifetimes (FARRAR 96) and production rates, which are assumed to be comparable to those of strange or charmed baryons.

[226] BARATE 97L studied the QCD color factors from four-jet angular correlations and the differential two-jet rate in Z decay. Limit obtained from the determination of n_f = 4.24 ± 0.29 ± 1.15, assuming T_F/C_F=3/8 and C_A/C_F=9/4.

[227] CSIKOR 97 combined the α_s from $\sigma(e^+e^- \rightarrow$ hadron), τ decay, and jet analysis in Z decay. They exclude a light gluino below 5 GeV at more than 99.7%CL.

[228] DEGOUVEA 97 reaanalyzed AKERS 95A data on Z decay into four jets to place constraints on a light stable gluino. The mass limit corresponds to the pole mass of 2.8 GeV. The analysis, however, is limited to the leading-order QCD calculation.

[229] FARRAR 96 studied the possible R^0=($\tilde{g}g$) component in Fermilab E799 experiment and used its bound B($K^0_L \rightarrow \pi^0 \nu\overline{\nu}$) $\leq 5.8 \times 10^{-5}$ to place constraints on the combination of R^0 production cross section and its lifetime.

[230] AKERS 95R looked for Z decay into $q\overline{q}\tilde{g}\tilde{g}$, by searching for charged particles with dE/dx consistent with $\tilde{g}$ fragmentation into a state $(\tilde{g}q\overline{q})^{\pm}$ with lifetime $\tau > 10^{-7}$ sec. The fragmentation probability into a charged state is assumed to be 25%.

[231] CLAVELLI 95 updates the analysis of CLAVELLI 93, based on a comparison of the hadronic widths of charmonium and bottomonium S-wave states. The analysis includes a parametrization of relativisitic corrections. Claims that the presence of a light gluino improves agreement with the data by slowing down the running of α_s.

[232] CAKIR 94 reanalyzed TUTS 87 and later unpublished data from CUSB to exclude pseudo-scalar gluinonium $\eta_{\tilde{g}}(\tilde{g}\tilde{g})$ of mass below 7 GeV. It was argued, however, that the perturbative QCD calculation of the branching fraction $\Upsilon \rightarrow \eta_{\tilde{g}}\gamma$ is unreliable for $m_{\eta_{\tilde{g}}} < 3$ GeV. The gluino mass is defined by $m_{\tilde{g}}$=($m_{\eta_{\tilde{q}}}$)/2. The limit holds for any gluino lifetime.

[233] LOPEZ 93C uses combined restraint from the radiative symmetry breaking scenario within the minimal supergravity model, and the LEP bounds on the (M_2,μ) plane. Claims that the light gluino window is strongly disfavored.

[234] CLAVELLI 92 claims that a light gluino mass around 4 GeV should exist to explain the discrepancy between α_s at LEP and at quarkonia (Υ), since a light gluino slows the running of the QCD coupling.

[235] ANTONIADIS 91 argue that possible light gluinos (< 5 GeV) contradict the observed running of α_s between 5 GeV and m_Z. The significance is less than 2 s.d.

[236] ANTONIADIS 91 intrepret the search for missing energy events in 450 GeV/c pN collisions, AKESSON 91, in terms of light gluinos.

[237] The limits assume $m_{\tilde{q}} = 100$ GeV. See their figure 3 for limits vs. $m_{\tilde{q}}$.

[238] The gluino mass is defined by half the bound $\tilde{g}\tilde{g}$ mass. If zero gluino mass gives a $\tilde{g}\tilde{g}$ of mass about 1 GeV as suggested by various glueball mass estimates, then the low-mass bound can be replaced by zero. The high-mass bound is obtained by comparing the data with nonrelativistic potential-model estimates.

[239] ALBRECHT 86C search for secondary decay vertices from $\chi_{b1}(1P) \rightarrow \tilde{g}\tilde{g}g$ where $\tilde{g}$'s make long-lived hadrons. See their figure 4 for excluded region in the $m_{\tilde{g}} - m_{\tilde{g}}$ and $m_{\tilde{g}} - m_{\tilde{q}}$ plane. The lower $m_{\tilde{g}}$ region below ~ 2 GeV may be sensitive to fragmentation effects. Remark that the $\tilde{g}$-hadron mass is expected to be ~ 1 GeV (glueball mass) in the zero $\tilde{g}$ mass limit.

[240] BADIER 86 looked for secondary decay vertices from long-lived $\tilde{g}$-hadrons produced at 300 GeV π^- beam dump. The quoted bound assumes $\tilde{g}$-hadron nucleon total cross section of 10μb. See their figure 7 for excluded region in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane for several assumed total cross-section values.

[241] BARNETT 86 rule out light gluinos (m = 3–5 GeV) by calculating the monojet rate from gluino gluino gluon events (and from gluino gluino events) and by using UA1 data from $p\overline{p}$ collisions at CERN.

[242] VOLOSHIN 86 rules out stable gluino based on the cosmological argument that predicts too much hydrogen consisting of the charged stable hadron $\tilde{g}uud$. Quasi-stable ($\tau > 1. \times 10^{-7}$s) light gluino of $m_{\tilde{g}}$ <3 GeV is also ruled out by nonobservation of the stable charged particles, $\tilde{g}uud$, in high energy hadron collisions.

[243] COOPER-SARKAR 85B is BEBC beam-dump. Gluinos decaying in dump would yield $\tilde{\gamma}$'s in the detector giving neutral-current-like interactions. For $m_{\tilde{q}}$ >330 GeV, no limit is set.

[244] DAWSON 85 first limit from neutral particle search. Second limit based on FNAL beam dump experiment.

[245] FARRAR 85 points out that BALL 84 analysis applies only if the $\tilde{g}$'s decay before interacting, i.e. $m_{\tilde{q}}$ <80$m_{\tilde{g}}^{1.5}$. FARRAR 85 finds $m_{\tilde{g}}$ <0.5 not excluded for $m_{\tilde{q}}$ = 30–1000 GeV and $m_{\tilde{g}}$ <1.0 not excluded for $m_{\tilde{q}}$ = 100–500 GeV by BALL 84 experiment.

[246] GOLDMAN 85 use nonobservation of a pseudoscalar $\tilde{g}$-$\tilde{g}$ bound state in radiative ψ decay.

[247] HABER 85 is based on survey of all previous searches sensitive to low mass $\tilde{g}$'s. Limit makes assumptions regarding the lifetime and electric charge of the lightest supersymmetric particle.

[248] BALL 84 is FNAL beam dump experiment. Observed no interactions of $\tilde{\gamma}$ in the calorimeter, where $\tilde{\gamma}$'s are expected to come from pair-produced $\tilde{g}$'s. Search for long-lived $\tilde{\gamma}$ interacting in calorimeter 56m from target. Limit is for $m_{\tilde{q}}$ = 40 GeV and production cross section proportional to $A^{0.72}$. BALL 84 find no $\tilde{g}$ allowed below 4.1 GeV at CL = 90%. Their figure 1 shows dependence on $m_{\tilde{q}}$ and A. See also KANE 82.

[249] BRICK 84 reanalyzed FNAL 147 GeV HBC data for R-$\Delta(1232)^{++}$ with $\tau > 10^{-9}$ s and p_{lab} >2 GeV. Set CL = 90% upper limits 6.1, 4.4, and 29 microbarns in pp, $\pi^+ p$, $K^+ p$ collisions respectively. R-Δ^{++} is defined as being $\tilde{g}$ and 3 up quarks. If mass = 1.2–1.5 GeV, then limits may be lower than theory predictions.

[250] FARRAR 84 argues that $m_{\tilde{g}}$ <100 MeV is not ruled out if the lightest R-hadrons are long-lived. A long lifetime would occur if R-hadrons are lighter than $\tilde{\gamma}$'s or if $m_{\tilde{q}}$ >100 GeV.

[251] BERGSMA 83C is reanalysis of CERN-SPS beam-dump data. See their figure 1.

[252] CHANOWITZ 83 find in bag-model that charged s-hadron exists which is stable against strong decay if $m_{\tilde{g}}$ <1 GeV. This is important since tracks from decay of neutral s-hadron cannot be reconstructed to primary vertex because of missed $\tilde{\gamma}$. Charged s-hadron leaves track from vertex.

[253] KANE 82 inferred above $\tilde{g}$ mass limit from retroactive analysis of hadronic collision and beam dump experiments. Limits valid if $\tilde{g}$ decays inside detector.

Supersymmetry Miscellaneous Results

Results that do not appear under other headings or that make nonminimal assumptions.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[254] ABACHI	97	D0	$\gamma\gamma X$
	[255] BARBER	84B	RVUE	
	[256] HOFFMAN	83	CNTR	$\pi p \rightarrow n(e^+ e^-)$

[254] ABACHI 97 searched for $p\overline{p} \rightarrow \gamma\gamma \not{E}_T$+$X$ as supersymmetry signature. It can be caused by selectron, sneutrino, or neutralino production with a radiative decay of their decay products. They placed limits on cross sections.

[255] BARBER 84B consider that $\tilde{\mu}$ and $\tilde{e}$ may mix leading to $\mu \rightarrow e\tilde{\gamma}\tilde{\gamma}$. They discuss mass-mixing limits from decay dist asym in LBL-TRIUMF data and e^+ polarization in SIN data.

[256] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B($e^+ e^-$) $< 3.5 \times 10^{-32}$ cm^2/GeV^2 for spin-1 partner of Goldstone fermions with 140 <m <160 MeV decaying → $e^+ e^-$ pair.

REFERENCES FOR Supersymmetric Particle Searches

ABBOTT 98 PRL 80 442 B. Abbott+ (D0 Collab.)
ABBOTT 98C PRL 80 1591 B. Abbott+ (D0 Collab.)
ABREU 98 EPJ C1 1 P. Abreu+ (DELPHI Collab.)
ACCIARRI 98F EPJ C (to be publ.) M. Acciarri+ (L3 Collab.)
CERN-PPE/97-130
ACKERSTAFF 98J EPJ C (to be publ.) K. Ackerstaff+ (OPAL Collab.)
CERN-PPE/97-132
ACKERSTAFF 98K EPJ C (to be publ.) K. Ackerstaff+ (OPAL Collab.)
CERN-PPE/97-124
ACKERSTAFF 98L EPJ C2 213 K. Ackerstaff+ (OPAL Collab.)
ABACHI 97 PRL 78 2070 S. Abachi+ (D0 Collab.)
ABE 97K PR D56 R1357 F. Abe+ (CDF Collab.)
ABREU 97D PL B396 315 P. Abreu+ (DELPHI Collab.)
ABREU 97J ZPHY C74 577 P. Abreu+ (DELPHI Collab.)
ACCIARRI 97U PL B414 373 M. Acciarri+ (L3 Collab.)
ACCIARRI 97V PL B415 299 M. Acciarri+ (L3 Collab.)
ACKERSTAFF 97H PL B396 301 K. Ackerstaff+ (OPAL Collab.)
ACKERSTAFF 97Q ZPHY C75 409 K. Ackerstaff+ (OPAL Collab.)
ADAMS 97B PRL 79 4083 J. Adams+ (KTeV Collab.)
ALBUQUERQ... 97 PRL 78 3252 I.F. Albuquerque+ (FNAL E761 Collab.)
ALEXANDER 97B ZPHY C73 201 G. Alexander+ (OPAL Collab.)
BARATE 97K PL B405 379 R. Barate+ (ALEPH Collab.)
BARATE 97L ZPHY C76 1 R. Barate+ (ALEPH Collab.)
BARATE 97N PL B407 377 R. Barate+ (ALEPH Collab.)
BARATE 97Q PL B413 431 R. Barate+ (ALEPH Collab.)
BOTTINO 97 PL B402 113 + (TORI, LAPP, GENO, ROMA, ROMA2, INFN)
CARENA 97 PL B390 234 M. Carena, G.F. Giudice, C.E.M. Wagner
CSIKOR 97 PRL 78 4335 F. Csikor, Z. Fodor (EOTV, CERN)
DATTA 97 PL B395 54 A. Datta, M. Guchait, N. Parua (ICTP, TATA)
DEGOUVEA 97 PL B400 117 A. de Gouvea, H. Murayama
DERRICK 97 ZPHY C73 613 M. Derrick+ (ZEUS Collab.)
ELLIS 97 PL B394 354 J. Ellis, J.L. Lopez, D.V. Nanopoulos
ELLIS 97C PL B413 355 J. Ellis, Falk, Olive, Schmitt
HEWETT 97 PR D56 5703 J.L. Hewett, T.G. Rizzo, M.A. Doncheski
KALINOWSKI 97 PL B400 112 J. Kalinowski, P. Zerwas
TEREKHOV 97 PL B412 86 I. Terekhov (ALAT)
ABACHI 96 PRL 76 2228 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABACHI 96B PRL 76 2222 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABE 96 PRL 77 438 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96D PRL 76 2006 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABE 96K PRL 76 4307 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABREU 96L PL B382 323 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 96O PL B387 651 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 96F PL B377 289 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ACKERSTAFF 96 PL B389 197 +Alexander, Allison, Altekamp+ (OPAL Collab.)
ACKERSTAFF 96C PL B389 616 +Alexander, Allison, Altekamp+ (OPAL Collab.)
AID 96 ZPHY C71 211 +Andreev, Andrieu, Appuhn+ (H1 Collab.)
AID 96C PL B380 461 +Andreev, Andrieu, Appuhn+ (H1 Collab.)
ALCARAZ 96 CERN-PPE/96-183 J. Alcaraz+
The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and the LEP Electroweak Working Group
ALEXANDER 96J PL B377 181 +Allison, Altekamp, Ametewee+ (OPAL Collab.)
ALEXANDER 96L PL B377 273 +Allison, Altekamp, Ametewee+ (OPAL Collab.)
BUSKULIC 96A ZPHY C72 549 D. Buskulic+ (ALEPH Collab.)
BUSKULIC 96K PL B373 246 +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
BUSKULIC 96U PL B384 461 +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
CHO 96 PL B372 101 +Kizukuri, Oshimo (TOKAH, OCH)
ELLIS 96B PL B388 97 +Falk, Olive, Schmitt (CERN, MINN)
FARRAR 96 PRL 76 4111 G.R. Farrar (RUTG)
SUGIMOTO 96 PL B369 86 +Abe, Fujii, Igarashi+ (AMY Collab.)
TEREKHOV 96 PL B385 139 I. Terkhov, L. Clavelli (ALAT)
ABACHI 95C PRL 75 618 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABE 95A PL B361 199 +Fujii, Sugiyama, Fujimoto+ (TOPAZ Collab.)
ABE 95N PRL 74 3538 +Albrow, Amendolia, Amidei, Antos+ (CDF Collab.)
ABE 95T PRL 75 613 +Albrow, Amidei, Anway-Wiese+ (CDF Collab.)
ACCIARRI 95E PL B350 109 +Adam, Adraiani, Aguilar-Benitez+ (L3 Collab.)
AKERS 95A ZPHY C65 367 R. Akers+ (OPAL Collab.)
AKERS 95R ZPHY C67 203 +Alexander, Allison, Ametewee, Anderson+ (OPAL Collab.)
BUSKULIC 95E PL B349 238 +Casper, DeBonis, Decamp+ (ALEPH Collab.)
CLAVELLI 95 PR D51 1117 +Coulter (ALAT)
FALK 95 PL B354 99 +Olive, Srednicki (MINN, UCSB)
LOSECCO 95 PL B342 392 (NDAM)
AHMED 94B ZPHY C64 545 +Aid, Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
AKERS 94K PL B337 207 +Alexander, Allison, Anderson+ (OPAL Collab.)
BECK 94 PL B336 141 +Bensch, Bockholt+ (MPIH, KIAE, SASSO)
CAKIR 94 PR D50 3268 M.B. Cakir, G.R. Farrar (RUTG)
FALK 94 PL B339 248 +Olive, Srednicki (UCSB, MINN)
FRANKE 94 PL B336 415 +Fraas, Bartl (WURZ, WIEN)
HOSODA 94 PL B331 211 +Abe, Amako, Arai+ (VENUS Collab.)
SHIRAI 94 PRL 72 3313 +Ohmoto, Abe, Amako+ (VENUS Collab.)
ACTON 93G PL B313 333 +Akers, Alexander, Allison, Anderson+ (OPAL Collab.)
ADRIANI 93M PRPL 236 1 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ALITTI 93 NP B400 3 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
CLAVELLI 93 PR D47 1973 +Coulter, Yuan (ALAT)
DREES 93 PR D47 376 +Nojiri (DESY, SLAC)
FALK 93 PL B318 354 +Madden, Olive, Srednicki (UCB, UCSB, MINN)
HEBBEKER 93 ZPHY C60 63 (CERN)
KELLEY 93 PR D47 2461 +Lopez, Nanopoulos, Pois, Yuan (TAMU, ALAH)
LAU 93 PR D47 1087 (HOUS)
LOPEZ 93C PL B313 241 +Nanopoulos, Wang (TAMU, HARC, CERN)
MIZUTA 93 PL B298 120 +Yamaguchi (TOHO)
MORI 93 PR D48 5505 +(KEK, NIIG, TOKY, TOKA, KOBE, OSAK, TINT, GIFU)
ABE 92L PRL 69 3439 +Amidei, Anway-Wiese, Apollinari, Atac+ (CDF Collab.)
BOTTINO 92 MPL A7 733 +DeAlfaro, Fornengo, Morales, Puimedon+ (TORI, ZARA)
Also 91 PL B265 57 Bottino, de Alfaro, Fornengo, Mignola+ (TORI, INFN)
CLAVELLI 92 PR D46 2112 (ALAT)
DECAMP 92 PRPL 216 253 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ELLIS 92F PL B283 252 +Roszkowski (CERN)
KAWASAKI 92 PR D46 1634 +Mizuta (OSU, TOHO)
LOPEZ 92 NP B370 445 +Nanopoulos, Yuan (TAMU)
MCDONALD 92 PL B283 80 +Olive, Srednicki (LISB, MINN, UCSB)
ROY 92 PL B283 270 (CERN)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
AKESSON 91 ZPHY C52 219 +Almehed, Angelis, Atherton, Aubry+ (HELIOS Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)

ANTONIADIS 91 PL B262 109 +Ellis, Nanopoulos (EPOL, CERN, TAMU, HARC)
BAER 91 PR D44 207 +Tata, Woodside (FSU, HAWA, ISU)
BOTTINO 91 PL B265 57 +de Alfaro, Fornengo, Mignola+ (TORI, INFN)
GELMINI 91 NP B351 623 +Gondolo, Roulet (UCLA, TRST)
HIDAKA 91 PR D44 927 (TGAK)
KAMIONKOW... 91 PR D44 3021 Kamionkowski (CHIC, FNAL)
MORI 91B PL B270 89 +Nojiri, Oyama, Suzuki+ (Kamiokande Collab.)
NOJIRI 91 PL B261 76 (KEK)
OLIVE 91 NP B355 208 +Srednicki (MINN, UCSB)
ROSZKOWSKI 91 PL B262 59 (CERN)
SATO 91 PR D44 2220 +Hirata, Kajita, Kifune, Kihara+ (Kamioka Collab.)
ABREU 90F PL B247 148 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90G PL B247 157 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 90I PL B249 341 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
AKESSON 90B PL B238 442 +Alitti, Ansari, Ansorge+ (UA2 Collab.)
AKRAWY 90D PL B240 261 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90N PL B248 211 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALITTI 90 PL B235 363 +Ansari, Ansorge, Bagnaia, Bareyre+ (UA2 Collab.)
BAER 90 PR D41 3414 +Drees, Tata (FSU, CERN, HAWA)
BARKLOW 90 PRL 64 2984 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
DECAMP 90C PL B236 86 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90K PL B244 541 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
ELLIS 90 PL B245 251 +Nanopoulos, Roszkowski, Schramm (CERN, HARC, TAMU)
GRIEST 90 PR D41 3565 +Kamionkowski, Turner (UCB, CHIC, FNAL)
GRIFOLS 90 NP B331 244 +Masso (BARC)
KRAUSS 90 PRL 64 999 (YALE)
SAKAI 90 PL B234 534 +Gu, Low, Abe, Fujii+ (AMY Collab.)
SODERSTROM 90 PRL 64 2980 +McKenna, Abrams, Adolphsen, Averill+ (Mark II Collab.)
TAKETANI 90 PL B234 202 +Odaka, Abe, Amako+ (VENUS Collab.)
ZHUKOVSKII 90 SJNP 52 931 +Eminov (MOSU)
Translated from YAF 52 1473.
ABE 89J ZPHY C45 175 +Amako, Arai, Fukawa+ (VENUS Collab.)
ADACHI 89 PL B218 105 +Aihara, Dijkstra, Enomoto, Fujii+ (TOPAZ Collab.)
ADEVA 89B PL B233 530 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
HEARTY 89 PR D39 3207 +Rothberg, Young, Johnson, Whitaker+ (ASP Collab.)
Also 87 PRL 58 1711 Hearty, Rothberg, Young, Johnson+ (ASP Collab.)
Also 86 PRL 56 685 Bartha, Burke, Extermann+ (ASP Collab.)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
OLIVE 89 PL B230 78 +Srednicki (MINN, UCSB)
BEHREND 88B PL B215 186 +Criegee, Dainton, Field+ (CELLO Collab.)
ELLIS 88B PL B215 404 +Olive, Sarkar, Sciama (CERN, MINN, RAL, CAMB)
NATH 88 PR D38 1479 +Arnowitt (NEAS, TAMU)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
ALBAJAR 87D PL B198 261 +Albrow, Allkofer+ (UA1 Collab.)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
ARNOLD 87 PL B186 435 +Barth+ (BRUX, DUUC, LOUC, BARI, AICH, CERN+)
BEHREND 87B ZPHY C35 181 +Buerger, Criegee, Dainton+ (CELLO Collab.)
NG 87 PL B188 138 +Olive, Srednicki (MINN, UCSB)
TUTS 87 PL B186 233 +Franzini, Youssef, Zhao+ (CUSB Collab.)
ALBRECHT 86C PL 167B 360 +Binder, Harder+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BARNETT 86 NP B267 625 +Haber, Kane (LBL, UCSC, MICH)
FORD 86 PR D33 3472 +Qi, Read+ (MAC Collab.)
GAISSER 86 PR D34 2206 +Steigman, Tilav (BART, DELA)
VOLOSHIN 86 SJNP 43 495 +Okun (ITEP)
Translated from YAF 43 779.
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
Also 84C PRPL 109 131 Adeva, Barber, Becker+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
BARTEL 85L PL 155B 288 +Becker, Cords, Felst, Hagiwara+ (JADE Collab.)
BEHREND 85 PL 161B 182 +Burger, Criegee, Fenner+ (CELLO Collab.)
COOPER-... 85B PL 160B 212 Cooper-Sarkar, Parker, Sarkar+ (WA66 Collab.)
DAWSON 85 PR D31 1581 +Eichten, Quigg (LBL, FNAL)
FARRAR 85 PRL 55 895 (RUTG)
GOLDMAN 85 Physica 15D 181 +Haber (LANL, UCSC)
HABER 85 PRPL 117 75 +Kane (UCSC, MICH)
ADEVA 84B PRL 53 1806 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BALL 84 PRL 53 1314 +Coffin, Gustafson+ (MICH, FIRZ, OSU, FNAL, WISC)
BARBER 84B PL 139B 427 +Shrock (STON)
BARTEL 84B PL 139B 327 +Becker, Bowdery, Cords+ (JADE Collab.)
BARTEL 84C PL 146B 126 +Becker, Bowdery, Cords+ (JADE Collab.)
BRICK 84 PR D30 1134 + (BROW, CAVE, IIT, IND, MIT, MONS, NIJM+)
ELLIS 84 NP B238 453 +Hagelin, Nanopoulos, Olive, Srednicki (CERN)
FARRAR 84 PRL 53 1029 (RUTG)
BEHREND 83 PL 123B 127 +Chen, Fenner, Gumpel+ (CELLO Collab.)
BERGSMA 83C PL 121B 429 +Dorenbosch, Jonker+ (CHARM Collab.)
CHANOWITZ 83 PL 126B 225 +Sharpe (UCB, LBL)
GOLDBERG 83 PRL 50 1419 (NEAS)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
KRAUSS 83 NP B227 556 (HARV)
VYSOTSKII 83 SJNP 37 948 (ITEP)
Translated from YAF 37 1597.
KANE 82 PL 112B 227 +Leveille (MICH)
CABIBBO 81 PL 105B 155 +Farrar, Maiani (ROMA, RUTG)
FARRAR 78 PL 76B 575 +Fayet (CIT)
Also 78B PL 79B 442 Farrar, Fayet (CIT)

Quark and Lepton Compositeness, Searches for

SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

Written 1994 by K. Hagiwara (KEK) and K. Hikasa (Tohoku Univ.).

If quarks and leptons are made of constituents, then at the scale of constituent binding energies, there should appear new interactions among quarks and leptons. At energies much below the compositeness scale (Λ), these interactions are suppressed by inverse powers of Λ. The dominant effect should come from the lowest dimensional interactions with four fermions (contact terms), whose most general chirally invariant form reads [1]

$$L = \frac{g^2}{2\Lambda^2}\Big[\eta_{LL}\overline{\psi}_L\gamma_\mu\psi_L\overline{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\overline{\psi}_R\gamma_\mu\psi_R\overline{\psi}_R\gamma^\mu\psi_R + 2\eta_{LR}\overline{\psi}_L\gamma_\mu\psi_L\overline{\psi}_R\gamma^\mu\psi_R\Big]\ . \qquad (1)$$

Chiral invariance provides a natural explanation why quark and lepton masses are much smaller than their inverse size Λ. We may determine the scale Λ unambiguously by using the above form of the effective interactions; the conventional method [1] is to fix its scale by setting $g^2/4\pi = g^2(\Lambda)/4\pi = 1$ for the new strong interaction coupling and by setting the largest magnitude of the coefficients $\eta_{\alpha\beta}$ to be unity. In the following, we denote

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, 0, 0)\ ,\\
\Lambda &= \Lambda^{\pm}_{RR} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0, \pm1, 0)\ ,\\
\Lambda &= \Lambda^{\pm}_{VV} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, \pm1, \pm1)\ ,\\
\Lambda &= \Lambda^{\pm}_{AA} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, \pm1, \mp1)\ , \qquad (2)
\end{aligned}$$

as typical examples. Such interactions can arise by constituent interchange (when the fermions have common constituents, e.g., for $ee \to ee$) and/or by exchange of the binding quanta (whenever binding quanta couple to constituents of both particles).

Another typical consequence of compositeness is the appearance of excited leptons and quarks (ℓ^* and q^*). Phenomenologically, an excited lepton is defined to be a heavy lepton which shares leptonic quantum number with one of the existing leptons (an excited quark is defined similarly). For example, an excited electron e^* is characterized by a nonzero transition-magnetic coupling with electrons. Smallness of the lepton mass and the success of QED prediction for g–2 suggest chirality conservation, *i.e.*, an excited lepton should not couple to both left- and right-handed components of the corresponding lepton.

Excited leptons may be classified by SU(2)×U(1) quantum numbers. Typical examples are:

1. Sequential type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L,\quad [\nu^*_R],\quad \ell^*_R\ .$$

ν^*_R is necessary unless ν^* has a Majorana mass.

2. Mirror type

$$[\nu^*_L],\quad \ell^*_L,\quad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R\ .$$

3. Homodoublet type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L,\quad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R\ .$$

Similar classification can be made for excited quarks.

Excited fermions can be pair produced via their gauge couplings. The couplings of excited leptons with Z are listed

	Sequential type	Mirror type	Homodoublet type
V^{ℓ^*}	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}+2\sin^2\theta_W$	$-1+2\sin^2\theta_W$
A^{ℓ^*}	$-\frac{1}{2}$	$+\frac{1}{2}$	0
$V^{\nu_D^*}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$+1$
$A^{\nu_D^*}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$V^{\nu_M^*}$	0	0	—
$A^{\nu_M^*}$	$+1$	-1	—

in the following table (for notation see Eq. (1) in "Standard Model of Electroweak Interactions"):

Here ν_D^* (ν_M^*) stands for Dirac (Majorana) excited neutrino. The corresponding couplings of excited quarks can be easily obtained. Although form factor effects can be present for the gauge couplings at $q^2 \neq 0$, they are usually neglected.

In addition, transition magnetic type couplings with a gauge boson are expected. These couplings can be generally parametrized as follows:

$$\begin{aligned}\mathcal{L} = {} & \frac{\lambda_\gamma^{(f^*)} e}{2m_{f^*}} \overline{f}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) f F_{\mu\nu} \\ & + \frac{\lambda_Z^{(f^*)} e}{2m_{f^*}} \overline{f}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) f Z_{\mu\nu} \\ & + \frac{\lambda_W^{(\ell^*)} g}{2m_{\ell^*}} \overline{\ell}^* \sigma^{\mu\nu} \tfrac{1-\gamma_5}{2} \nu W_{\mu\nu} \\ & + \frac{\lambda_W^{(\nu^*)} g}{2m_{\nu^*}} \overline{\nu}^* \sigma^{\mu\nu}(\eta_L \tfrac{1-\gamma_5}{2} + \eta_R \tfrac{1+\gamma_5}{2}) \ell W_{\mu\nu}^\dagger \\ & + \text{h.c.}\,, \end{aligned} \tag{3}$$

where $g = e/\sin\theta_W$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the photon field strength, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$, *etc.* The normalization of the coupling is chosen such that

$$\max(|\eta_L|, |\eta_R|) = 1\,.$$

Chirality conservation requires

$$\eta_L \eta_R = 0\,. \tag{4}$$

These couplings can arise from SU(2)×U(1)-invariant higher-dimensional interactions. A well-studied model is the interaction of homodoublet type ℓ^* with the Lagrangian [2,3]

$$\mathcal{L} = \frac{1}{2\Lambda} \overline{L}^* (g f \tfrac{\tau^a}{2} W^a_{\mu\nu} + g' f' Y B_{\mu\nu}) \tfrac{1-\gamma_5}{2} L + \text{h.c.}\,, \tag{5}$$

where L denotes the lepton doublet (ν, ℓ), Λ is the compositeness scale, g, g' are SU(2) and U(1)$_Y$ gauge couplings, and $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengths for SU(2) and U(1)$_Y$ gauge fields. The same interaction occurs for mirror-type excited leptons. For sequential-type excited leptons, the ℓ^* and ν^* couplings become unrelated, and the couplings receive the extra suppression of (250 GeV)/Λ or m_{L^*}/Λ. In any case, these couplings satisfy the relation

$$\lambda_W = -\sqrt{2}\sin^2\theta_W(\lambda_Z \cot\theta_W + \lambda_\gamma)\,. \tag{6}$$

Additional coupling with gluons is possible for excited quarks:

$$\begin{aligned}\mathcal{L} = {} & \frac{1}{2\Lambda} \overline{Q}^* \sigma^{\mu\nu} \left(g_s f_s \tfrac{\lambda^a}{2} G^a_{\mu\nu} + g\, f \tfrac{\tau^a}{2} W^a_{\mu\nu} + g'\, f' Y B_{\mu\nu} \right) \\ & \times \tfrac{1-\gamma_5}{2} Q + \text{h.c.}\,, \end{aligned} \tag{7}$$

where Q denotes a quark doublet, g_s is the QCD gauge coupling, and $G^a_{\mu\nu}$ the gluon field strength.

Some experimental analyses assume the relation $\eta_L = \eta_R = 1$, which violates chiral symmetry. We encode the results of such analyses if the crucial part of the cross section is proportional to the factor $\eta_L^2 + \eta_R^2$ and the limits can be reinterpreted as those for chirality conserving cases $(\eta_L, \eta_R) = (1, 0)$ or $(0, 1)$ after rescaling λ.

Several different conventions are used by LEP experiments to express the transition magnetic couplings. To facilitate comparison, we reexpress these in terms of λ_Z and λ_γ using the following relations and taking $\sin^2\theta_W = 0.23$. We assume chiral couplings, *i.e.*, $|c| = |d|$ in the notation of Ref. 2.

1. ALEPH (charged lepton and neutrino)

$$\lambda_Z^{\text{ALEPH}} = \frac{1}{2}\lambda_Z \quad \text{(1990 papers)} \tag{8a}$$

$$\frac{2c}{\Lambda} = \frac{\lambda_Z}{m_{\ell^*}[\text{or } m_{\nu^*}]} \quad (\text{for } |c| = |d|) \tag{8b}$$

2. ALEPH (quark)

$$\lambda_u^{\text{ALEPH}} = \frac{\sin\theta_W \cos\theta_W}{\sqrt{\frac{1}{4} - \frac{2}{3}\sin^2\theta_W + \frac{8}{9}\sin^4\theta_W}}\, \lambda_Z = 1.11\lambda_Z \tag{9}$$

3. L3 and DELPHI (charged lepton)

$$\lambda^{\text{L3}} = \lambda_Z^{\text{DELPHI}} = -\frac{\sqrt{2}}{\cot\theta_W - \tan\theta_W}\, \lambda_Z = -1.10\lambda_Z \tag{10}$$

4. L3 (neutrino)

$$f_Z^{\text{L3}} = \sqrt{2}\lambda_Z \tag{11}$$

5. OPAL (charged lepton)

$$\frac{f^{\text{OPAL}}}{\Lambda} = -\frac{2}{\cot\theta_W - \tan\theta_W}\, \frac{\lambda_Z}{m_{\ell^*}} = -1.56\, \frac{\lambda_Z}{m_{\ell^*}} \tag{12}$$

6. OPAL (quark)

$$\frac{f^{\text{OPAL}}c}{\Lambda} = \frac{\lambda_Z}{2m_{q^*}} \quad (\text{for } |c| = |d|) \tag{13}$$

7. DELPHI (charged lepton)

$$\lambda_\gamma^{\text{DELPHI}} = -\frac{1}{\sqrt{2}}\, \lambda_\gamma \tag{14}$$

If leptons are made of color triplet and antitriplet constituents, we may expect their color-octet partners. Transitions between the octet leptons (ℓ_8) and the ordinary lepton (ℓ) may take place via the dimension-five interactions

$$\mathcal{L} = \frac{1}{2\Lambda} \sum_{\ell} \left\{ \overline{\ell}_8^{\alpha}\, g_S\, F^{\alpha}_{\mu\nu}\, \sigma^{\mu\nu} \left(\eta_L\, \ell_L + \eta_R\, \ell_R \right) + h.c. \right\} \qquad (15)$$

where the summation is over charged leptons and neutrinos. The leptonic chiral invariance implies $\eta_L\, \eta_R = 0$ as before.

References

1. E.J. Eichten, K.D. Lane, and M.E. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
2. K. Hagiwara, S. Komamiya, and D. Zeppenfeld, Z. Phys. **C29**, 115 (1985).
3. N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. **139B**, 459 (1984).

SCALE LIMITS for Contact Interactions: $\Lambda(eeee)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 2.4	>2.2	95	ACKERSTAFF 97C	OPAL	E_{cm}= 130–136, 161 GeV
	>3.6	95	[1] KROHA 92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.7	>2.3	95	[2] ARIMA 97	VNS	E_{cm}= 57.77 GeV
>1.6	>2.0	95	[3] BUSKULIC 93Q	ALEP	E_{cm}=88.25–94.25 GeV
>1.6		95	[3,4] BUSKULIC 93Q	RVUE	
	>2.2	95	BUSKULIC 93Q	RVUE	
>1.3		95	[1] KROHA 92	RVUE	
>0.7	>2.8	95	BEHREND 91C	CELL	E_{cm}=35 GeV
>1.3	>1.3	95	KIM 89	AMY	E_{cm}=50–57 GeV
>1.4	>3.3	95	[5] BRAUNSCH... 88	TASS	E_{cm}=12–46.8 GeV
>1.0	>0.7	95	[6] FERNANDEZ 87B	MAC	E_{cm}=29 GeV
>1.1	>1.4	95	[7] BARTEL 86C	JADE	E_{cm}=12–46.8 GeV
>1.17	>0.87	95	[8] DERRICK 86	HRS	E_{cm}=29 GeV
>1.1	>0.76	95	[9] BERGER 85B	PLUT	E_{cm}=34.7 GeV

[1] KROHA 92 limit is from fit to BERGER 85B, BARTEL 86C, DERRICK 86B, FERNANDEZ 87B, BRAUNSCHWEIG 88, BEHREND 91B, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.230 \pm 0.206$ TeV^{-2}.

[2] Z-Z' mixing is assumed to be zero.

[3] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[4] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[5] BRAUNSCHWEIG 88 assumed $m_Z = 92$ GeV and $\sin^2\theta_W = 0.23$.

[6] FERNANDEZ 87B assumed $\sin^2\theta_W = 0.22$.

[7] BARTEL 86C assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

[8] DERRICK 86 assumed $m_Z = 93$ GeV and $g^2_V = (-1/2+2\sin^2\theta_W)^2 = 0.004$.

[9] BERGER 85B assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\mu\mu)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>2.4	**> 2.9**	95	ACKERSTAFF 97C	OPAL	E_{cm}= 130–136, 161 GeV
> 2.6	>1.9	95	[10,11] BUSKULIC 93Q	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.7	>2.2	95	[11] VELISSARIS 94	AMY	E_{cm}=57.8 GeV
>1.3	>1.5	95	[11] BUSKULIC 93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.3	>2.0	95	HOWELL 92	TOPZ	E_{cm}=52–61.4 GeV
	>1.7	95	[12] KROHA 92	RVUE	
>2.5	>1.5	95	BEHREND 91C	CELL	E_{cm}=35–43 GeV
>1.6	>2.0	95	[13] ABE 90I	VNS	E_{cm}=50–60.8 GeV
>1.9	>1.0	95	KIM 89	AMY	E_{cm}=50–57 GeV
>2.3	>1.3	95	BRAUNSCH... 88D	TASS	E_{cm}=30–46.8 GeV
>4.4	>2.1	95	[14] BARTEL 86C	JADE	E_{cm}=12–46.8 GeV
>2.9	>0.86	95	[15] BERGER 85	PLUT	E_{cm}=34.7 GeV

[10] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[11] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[12] KROHA 92 limit is from fit to BARTEL 86C, BEHREND 87C, BRAUNSCHWEIG 88D, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = -0.155 \pm 0.095$ TeV^{-2}.

[13] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[14] BARTEL 86C assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

[15] BERGER 85 assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\tau\tau)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1.9	**>3.0**	95	ACKERSTAFF 97C	OPAL	E_{cm}= 130–136, 161 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.4	>2.0	95	[16] VELISSARIS 94	AMY	E_{cm}=57.8 GeV
>1.0	>1.5	95	[16] BUSKULIC 93Q	ALEP	E_{cm}=88.25–94.25 GeV
>1.8	>2.3	95	[16,17] BUSKULIC 93Q	RVUE	
>1.9	>1.7	95	HOWELL 92	TOPZ	E_{cm}=52–61.4 GeV
>1.9	>2.9	95	[18] KROHA 92	RVUE	
>1.6	>2.3	95	BEHREND 91C	CELL	E_{cm}=35–43 GeV
>1.8	>1.3	95	[19] ABE 90I	VNS	E_{cm}=50–60.8 GeV
>2.2	>3.2	95	[20] BARTEL 86	JADE	E_{cm}=12–46.8 GeV

[16] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[17] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[18] KROHA 92 limit is from fit to BARTEL 86C BEHREND 89B, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.095 \pm 0.120$ TeV^{-2}.

[19] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[20] BARTEL 86 assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\ell\ell\ell)$

Lepton universality assumed. Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>2.7	**> 3.8**	95	ACKERSTAFF 97C	OPAL	E_{cm}= 130–136, 161 GeV
> 3.5	>2.8	95	[21,22] BUSKULIC 93Q	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.0	>2.3	95	[22,23] BUSKULIC 93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.5	>2.2	95	[24] HOWELL 92	TOPZ	E_{cm}=52–61.4 GeV
>3.4	>2.7	95	[25] KROHA 92	RVUE	

[21] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[22] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[23] From $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$.

[24] HOWELL 92 limit is from $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$.

[25] KROHA 92 limit is from fit to most PEP/PETRA/TRISTAN data. The fit gives $\eta/\Lambda^2_{LL} = -0.0200 \pm 0.0666$ TeV^{-2}.

SCALE LIMITS for Contact Interactions: $\Lambda(eeqq)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>2.5	**>3.7**	95	[26] ABE 97T	CDF	($eeqq$) (isosinglet)
>3.1	**>2.9**	95	[27] ACKERSTAFF 97C	OPAL	($eebb$)
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>2.5	>2.1	95	[28] ACKERSTAFF 97C	OPAL	($eeqq$)
>7.4	>11.7	95	[29] DEANDREA 97	RVUE	$eeuu$, atomic parity violation
>2.3	>1.0	95	[30] AID 95	H1	($eeqq$) (u, d quarks)
1.7	>2.2	95	[31] ABE 91D	CDF	($eeqq$) (u, d quarks)
>1.2		95	[32] ADACHI 91	TOPZ	($eeqq$) (flavor-universal)
	>1.6	95	[32] ADACHI 91	TOPZ	($eeqq$) (flavor-universal)
>0.6	>1.7	95	[33] BEHREND 91C	CELL	($eecc$)
>1.1	>1.0	95	[33] BEHREND 91C	CELL	($eebb$)
>0.9		95	[34] ABE 89L	VNS	($eeqq$) (flavor-universal)
	>1.7	95	[34] ABE 89L	VNS	($eeqq$) (flavor-universal)
>1.05	>1.61	95	[35] HAGIWARA 89	RVUE	($eecc$)
>1.21	>0.53	95	[36] HAGIWARA 89	RVUE	($eebb$)

[26] ABE 97T limits are from e^+e^- mass distribution in $\overline{p}p \rightarrow e^+e^-X$ at E_{cm}=1.8 TeV.

[27] ACKERSTAFF 97C limits are R_b measurements at E_{cm} = 133 GeV and 161 GeV.

[28] ACKERSTAFF 97C limits are from $e^+e^- \rightarrow q\overline{q}$ cross section at E_{cm} = 130–136 GeV and 161 GeV.

[29] DEANDREA 97 limit is from atomic parity violation of cesium. The limit is eluded if the contact interactions are parity conserving.

[30] AID 95 limits are from the Q^2 spectrum measurement of $ep \rightarrow eX$.

[31] ABE 91D limits are from e^+e^- mass distribution in $p\overline{p} \rightarrow e^+e^-X$ at E_{cm} = 1.8 TeV.

[32] ADACHI 91 limits are from differential jet cross section. Universality of $\Lambda(eeqq)$ for five flavors is assumed.

[33] BEHREND 91C is from data at E_{cm} = 35–43 GeV.

[34] ABE 89L limits are from jet charge asymmetry. Universality of $\Lambda(eeqq)$ for five flavors is assumed.

[35] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurements of D/D^* mesons by ALTHOFF 83C, BARTEL 84E, and BARINGER 88.

[36] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurement of b hadrons by BARTEL 84D.

SCALE LIMITS for Contact Interactions: $\Lambda(\mu\mu q q)$

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.9	>4.2	95	[37] ABE	97T	CDF	$(\mu\mu q q)$ (isosinglet)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.4	>1.6	95	ABE	92B	CDF	$(\mu\mu q q)$ (isosinglet)

[37] ABE 97T limits are from $\mu^+\mu^-$ mass distribution in $\overline{p}p \to \mu^+\mu^- X$ at $E_{\rm cm}$=1.8 TeV.

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\nu\ell\nu)$

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[38] JODIDIO	86	SPEC	$\Lambda^{\pm}_{LR}(\nu_\mu \nu_e \mu e)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.8		[39] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau e\nu_e)$
>8.1		[39] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau e\nu_e)$
>4.1		[40] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau \mu\nu_\mu)$
>6.5		[40] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau \mu\nu_\mu)$

[38] JODIDIO 86 limit is from $\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$. Chirality invariant interactions $L = (g^2/\Lambda^2)$ $[\eta_{LL}\,(\overline{\nu}_{\mu L}\gamma^\alpha \mu_L)\,(\overline{e}_L\gamma_\alpha \nu_{eL}) + \eta_{LR}\,(\overline{\nu}_{\mu L}\gamma^\alpha \nu_{eL}\,(\overline{e}_R\gamma_\alpha \mu_R)]$ with $g^2/4\pi = 1$ and $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ are taken. No limits are given for $\Lambda^{\pm}_{LL}$ with $(\eta_{LL},\eta_{LR}) = (\pm1,0)$. For more general constraints with right-handed neutrinos and chirality nonconserving contact interactions, see their text.

[39] DIAZCRUZ 94 limits are from $\Gamma(\tau \to e\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau e\nu_e) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

[40] DIAZCRUZ 94 limits are from $\Gamma(\tau \to \mu\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau \mu\nu_\mu) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$

Limits are for $\Lambda^{\pm}_{LL}$ with color-singlet isoscalar exchanges among u_L's and d_L's only. See EICHTEN 84 for details.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
		[41] ABE	96	CDF	$p\overline{p} \to$ jets inclusive
>1.6	95	[42] ABE	96S	CDF	$p\overline{p} \to$ dijet angl.; Λ^+_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.3	95	[43] ABE	93G	CDF	$p\overline{p} \to$ dijet mass
>1.4	95	[44] ABE	92D	CDF	$p\overline{p} \to$ jets inclusive
>1.0	99	[45] ABE	92M	CDF	$p\overline{p} \to$ dijet angl.
>0.825	95	[46] ALITTI	91B	UA2	$p\overline{p} \to$ jets inclusive
>0.700	95	[44] ABE	89	CDF	$p\overline{p} \to$ jets inclusive
>0.330	95	[47] ABE	89H	CDF	$p\overline{p} \to$ dijet angl.
>0.400	95	[48] ARNISON	86C	UA1	$p\overline{p} \to$ jets inclusive
>0.415	95	[49] ARNISON	86D	UA1	$p\overline{p} \to$ dijet angl.
>0.370	95	[50] APPEL	85	UA2	$p\overline{p} \to$ jets inclusive
>0.275	95	[51] BAGNAIA	84C	UA2	Repl. by APPEL 85

[41] ABE 96 finds that the inclusive jet cross section for E_T >200 GeV is significantly higher than the $\mathcal{O}(\alpha_s^3)$ perturbative QCD prediction. This could be interpreted as the effect of a contact interaction with Λ_{LL} ~ 1.6 TeV. However, ABE 96 state that uncertainty in the parton distribution functions, higher-order QCD corrections, and the detector calibration may possibly account for the effect.

[42] ABE 96S limit is from dijet angular distribution in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.8 TeV. The limit for Λ^-_{LL} is > 1.4 TeV. ABE 96S also obtain limits for flavor symmetric contact interactions among all quark flavors: Λ^+_{LL} > 1.8 TeV and Λ^-_{LL} > 1.6 TeV.

[43] ABE 93G limit is from dijet mass distribution in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.8 TeV. The limit is the weakest from several choices of structure functions and renormalization scale.

[44] Limit is from inclusive jet cross-section data in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.8 TeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[45] ABE 92M limit is from dijet angular distribution for $m_{\rm dijet}$ >550 GeV in $p\overline{p}$ collisions at $E_{\rm cm}$=1.8 TeV.

[46] ALITTI 91B limit is from inclusive jet cross section in $p\overline{p}$ collisions at $E_{\rm cm}$ = 630 GeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[47] ABE 89H limit is from dijet angular distribution for $m_{\rm dijet}$ > 200 GeV at the Fermilab Tevatron Collider with $E_{\rm cm}$ = 1.8 TeV. The QCD prediction is quite insensitive to choice of structure functions and choice of process scale.

[48] ARNISON 86C limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{\rm cm}$ = 546 and 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good fit to the data.

[49] ARNISON 86D limit is from the study of dijet angular distribution in the range 240 < m(dijet) < 300 GeV at the CERN $\overline{p}p$ collider ($E_{\rm cm}$ = 630 GeV). QCD prediction using EHLQ structure function (EICHTEN 84) with $\Lambda_{\rm QCD}$ = 0.2 GeV for the choice of $Q^2 = {p_T}^2$ gives the best fit to the data.

[50] APPEL 85 limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{\rm cm}$ = 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good description of the data.

[51] BAGNAIA 84C limit is from the study of jet p_T and dijet mass distributions at the CERN $\overline{p}p$ collider ($E_{\rm cm}$ = 540 GeV). The limit suffers from the uncertainties in comparing the data with the QCD prediction.

MASS LIMITS for Excited e (e^*)

Most e^+e^- experiments assume one-photon or Z exchange. The limits from some e^+e^- experiments which depend on λ have assumed transition couplings which are chirality violating ($\eta_L = \eta_R$). However they can be interpreted as limits for chirality-conserving interactions after multiplying the coupling value λ by $\sqrt{2}$; see Note.

Excited leptons have the same quantum numbers as other ortholeptons. See also the searches for ortholeptons in the "Searches for Heavy Leptons" section.

Limits for Excited e (e^*) from Pair Production

These limits are obtained from $e^+e^- \to e^{*+}e^{*-}$ and thus rely only on the (electroweak) charge of e^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the e^* coupling is assumed to be of sequential type. Possible t channel contribution from transition magnetic coupling is neglected. All limits assume $e^* \to e\gamma$ decay except the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>85.0	95	[52] ACKERSTAFF	98C	OPAL	$e^+e^- \to e^*e^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>79.6	95	[53,54] ABREU	97B	DLPH	$e^+e^- \to e^*e^*$ Homodoublet type
>77.9	95	[53,55] ABREU	97B	DLPH	$e^+e^- \to e^*e^*$ Sequential type
>79.7	95	[53] ACCIARRI	97G	L3	$e^+e^- \to e^*e^*$ Sequential type
>79.9	95	[53,56] ACKERSTAFF	97	OPAL	$e^+e^- \to e^*e^*$ Homodoublet type
>62.5	95	[57] ABREU	96K	DLPH	$e^+e^- \to e^*e^*$ Homodoublet type
>64.7	95	[58] ACCIARRI	96D	L3	$e^+e^- \to e^*e^*$ Sequential type
>66.5	95	[58] ALEXANDER	96Q	OPAL	$e^+e^- \to e^*e^*$ Homodoublet type
>65.2	95	[58] BUSKULIC	96W	ALEP	$e^+e^- \to e^*e^*$ Sequential type
>45.6	95	ADRIANI	93M	L3	$Z \to e^*e^*$
>45.6	95	ABREU	92C	DLPH	$Z \to e^*e^*$
>29.8	95	[59] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[60] DECAMP	92	ALEP	$Z \to e^*e^*$; $\Gamma(Z)$
>46.1	95	DECAMP	92	ALEP	$Z \to e^*e^*$
>33	95	[60] ABREU	91F	DLPH	$Z \to e^*e^*$; $\Gamma(Z)$
>45.0	95	[61] ADEVA	90F	L3	$Z \to e^*e^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to e^*e^*$
>44.6	95	[62] DECAMP	90G	ALEP	$e^+e^- \to e^*e^*$
>30.2	95	ADACHI	89B	TOPZ	$e^+e^- \to e^*e^*$
>28.3	95	KIM	89	AMY	$e^+e^- \to e^*e^*$
>27.9	95	[63] ABE	88B	VNS	$e^+e^- \to e^*e^*$

[52] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $e^* \to \nu W$ decay mode: $m_{e^*} > 81.3$ GeV.

[53] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[54] ABREU 97B also obtain limit from charged current decay mode $e^* \to \nu W$, $m_{e^*} > 70.9$ GeV.

[55] ABREU 97B also obtain limit from charged current decay mode $e^* \to \nu W$, $m_{e^*} > 44.6$ GeV.

[56] ACKERSTAFF 97 also obtain limit from charged current decay mode $e^* \to \nu W$, $m_{\nu_e^*} >$ 77.1 GeV.

[57] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[58] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[59] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.

[60] Limit is independent of e^* decay mode.

[61] ADEVA 90F is superseded by ADRIANI 93M.

[62] Superseded by DECAMP 92.

[63] ABE 88B limits assume $e^+e^- \to e^{*+}e^{*-}$ with one photon exchange only and $e^* \to e\gamma$ giving $ee\gamma\gamma$.

Limits for Excited e (e^*) from Single Production

These limits are from $e^+e^- \to e^*e$, $W \to e^*\nu$, or $ep \to e^*X$ and depend on transition magnetic coupling between e and e^*. All limits assume $e^* \to e\gamma$ decay except as noted. Limits from LEP, UA2, and H1 are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{e^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 30–200	95	[64] BREITWEG	97C	ZEUS	$ep \to e^*X$
>89	95	ADRIANI	93M	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>88	95	ABREU	92C	DLPH	$Z \to ee^*$, $\lambda_Z > 0.5$
>91	95	DECAMP	92	ALEP	$Z \to ee^*$, $\lambda_Z >1$
>87	95	AKRAWY	90I	OPAL	$Z \to ee^*$, $\lambda_Z > 0.5$

• • • We do not use the following data for averages, fits, limits, etc. • • •

	95	[65] ACKERSTAFF 98C	OPAL	$e^+e^- \to ee^*$
		[66,67] ABREU 97B	DLPH	$e^+e^- \to ee^*$
		[66,68] ACCIARRI 97G	L3	$e^+e^- \to ee^*$
		[69] ACKERSTAFF 97	OPAL	$e^+e^- \to ee^*$
		[70] ADLOFF 97	H1	Lepton-flavor violation
		[71] ABREU 96K	DLPH	$e^+e^- \to ee^*$
		[72] ACCIARRI 96D	L3	$e^+e^- \to ee^*$
		[73] ALEXANDER 96Q	OPAL	$e^+e^- \to ee^*$
		[74] BUSKULIC 96W	ALEP	$e^+e^- \to ee^*$
		[75] DERRICK 95B	ZEUS	$ep \to e^* X$
		[76] ABT 93	H1	$ep \to e^* X$
>86	95	ADRIANI 93M	L3	$\lambda_\gamma > 0.04$
		[77] DERRICK 93B	ZEUS	Superseded by DERRICK 95B
>86	95	ABREU 92C	DLPH	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.1$
>88	95	[78] ADEVA 90F	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>86	95	[78] ADEVA 90F	L3	$Z \to ee^*$, $\lambda_Z > 0.04$
>81	95	[79] DECAMP 90G	ALEP	$Z \to ee^*$, $\lambda_Z > 1$
>50	95	ADACHI 89B	TOPZ	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.04$
>56	95	KIM 89	AMY	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.03$
none 23–54	95	[80] ABE 88B	VNS	$e^+e^- \to ee^*$ $\lambda_\gamma > 0.04$
>75	95	[81] ANSARI 87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.7$
>63	95	[81] ANSARI 87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.2$
>40	95	[81] ANSARI 87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.09$

[64] BREITWEG 97C search for single e^* production in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. $f=-f'=2\Lambda/m_{e^*}$ is assumed for the e^* coupling. See their Fig. 9 for the exclusion plot in the mass-coupling plane.

[65] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[66] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[67] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.

[68] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[69] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[70] ADLOFF 97 search for single e^* production in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 4 for the rejection limits on the product of the production cross section and the branching ratio into a specific decay channel.

[71] ABREU 96K result is from e^+e^- collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[72] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[73] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.

[74] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[75] DERRICK 95B search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 13 for the exclusion plot in the m_{e^*}–$\lambda\gamma$ plane.

[76] ABT 93 search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 4 for exclusion plot in the m_{e^*}–λ_γ plane.

[77] DERRICK 93B search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 3 for exclusion plot in the m_{e^*}–λ_γ plane.

[78] Superseded by ADRIANI 93M.

[79] Superseded by DECAMP 92.

[80] ABE 88B limits use $e^+e^- \to ee^*$ where t-channel photon exchange dominates giving $e\gamma(e)$ (quasi-real compton scattering).

[81] ANSARI 87D is at $E_{\rm cm}$ = 546–630 GeV.

Limits for Excited e (e^*) from $e^+e^- \to \gamma\gamma$

These limits are derived from indirect effects due to e^* exchange in the t channel and depend on transition magnetic coupling between e and e^*. All limits are for $\lambda_\gamma = 1$. All limits except ABE 89J are for nonchiral coupling with $\eta_L = \eta_R = 1$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>194	95	ACKERSTAFF 98	OPAL	$\sqrt{s}$=130–172 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>129	95	ACCIARRI 96L	L3	$\sqrt{s}$=133 GeV
>147	95	ALEXANDER 96K	OPAL	
>136	95	BUSKULIC 96Z	ALEP	$\sqrt{s}$=130, 136 GeV
>146	95	ACCIARRI 95G	L3	
		[82] BUSKULIC 93Q	ALEP	
>127	95	[83] ADRIANI 92B	L3	
>114	95	[84] BARDADIN-... 92	RVUE	
> 99	95	DECAMP 92	ALEP	
		[85] SHIMOZAWA 92	TOPZ	
>100	95	ABREU 91E	DLPH	
>116	95	AKRAWY 91F	OPAL	
> 83	95	ADEVA 90K	L3	
> 82	95	AKRAWY 90F	OPAL	
> 68	95	[86] ABE 89J	VNS	η_L=1, η_R=0
> 90.2	95	ADACHI 89B	TOPZ	
> 65	95	KIM 89	AMY	

[82] BUSKULIC 93Q obtain Λ^+ >121 GeV (95%CL) from ALEPH experiment and Λ^+ >135 GeV from combined TRISTAN and ALEPH data. These limits roughly correspond to limits on m_{e^*}.

[83] ADRIANI 92B superseded by ACCIARRI 95G.

[84] BARDADIN-OTWINOWSKA 92 limit from fit to the combined data of DECAMP 92, ABREU 91E, ADEVA 90K, AKRAWY 91F.

[85] SHIMOZAWA 92 fit the data to the limiting form of the cross section with $m_{e^*} \gg E_{cm}$ and obtain m_{e^*} >168 GeV at 95%CL. Use of the full form would reduce this limit by a few GeV. The statistically unexpected large value is due to fluctuation in the data.

[86] The ABE 89J limit assumes chiral coupling. This corresponds to $\lambda_\gamma = 0.7$ for nonchiral coupling.

Indirect Limits for Excited e (e^*)

These limits make use of loop effects involving e^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[87] DORENBOS... 89	CHRM	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$
	[88] GRIFOLS 86	THEO	$\nu_\mu e \to \nu_\mu e$
	[89] RENARD 82	THEO	$g-2$ of electron

[87] DORENBOSCH 89 obtain the limit $\lambda_\gamma^2 \Lambda_{\rm cut}^2/m_{e^*}^2 < 2.6$ (95% CL), where $\Lambda_{\rm cut}$ is the cutoff scale, based on the one-loop calculation by GRIFOLS 86. If one assumes that $\Lambda_{\rm cut}$ = 1 TeV and $\lambda_\gamma = 1$, one obtains m_{e^*} > 620 GeV. However, one generally expects $\lambda_\gamma \approx m_{e^*}/\Lambda_{\rm cut}$ in composite models.

[88] GRIFOLS 86 uses $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ data from CHARM Collaboration to derive mass limits which depend on the scale of compositeness.

[89] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited μ (μ^*)

Limits for Excited μ (μ^*) from Pair Production

These limits are obtained from $e^+e^- \to \mu^{*+}\mu^{*-}$ and thus rely only on the (electroweak) charge of μ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the μ^* coupling is assumed to be of sequential type. All limits assume $\mu^* \to \mu\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>85.3	95	[90] ACKERSTAFF 98C	OPAL	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>79.6	95	[91,92] ABREU 97B	DLPH	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
>78.4	95	[91,93] ABREU 97B	DLPH	$e^+e^- \to \mu^*\mu^*$ Sequential type
>79.9	95	[91] ACCIARRI 97G	L3	$e^+e^- \to \mu^*\mu^*$ Sequential type
>80.0	95	[91,94] ACKERSTAFF 97	OPAL	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
>62.6	95	[95] ABREU 96K	DLPH	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
>64.9	95	[96] ACCIARRI 96D	L3	$e^+e^- \to \mu^*\mu^*$ Sequential type
>66.8	95	[96] ALEXANDER 96Q	OPAL	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
>65.4	95	[96] BUSKULIC 96W	ALEP	$e^+e^- \to \mu^*\mu^*$ Sequential type
>45.6	95	ADRIANI 93M	L3	$Z \to \mu^*\mu^*$
>45.6	95	ABREU 92C	DLPH	$Z \to \mu^*\mu^*$
>29.8	95	[97] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>26.1	95	[98] DECAMP 92	ALEP	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>46.1	95	DECAMP 92	ALEP	$Z \to \mu^*\mu^*$
>33	95	[98] ABREU 91F	DLPH	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>45.3	95	[99] ADEVA 90F	L3	$Z \to \mu^*\mu^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \to \mu^*\mu^*$
>44.6	95	[100] DECAMP 90G	ALEP	$e^+e^- \to \mu^*\mu^*$
>29.9	95	ADACHI 89B	TOPZ	$e^+e^- \to \mu^*\mu^*$
>28.3	95	KIM 89	AMY	$e^+e^- \to \mu^*\mu^*$

[90] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $\mu^* \to \nu W$ decay mode: $m_{\mu^*} > 81.3$ GeV.

[91] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[92] ABREU 97B also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\mu^*} > 70.9$ GeV.

[93] ABREU 97B also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\mu^*} > 44.6$ GeV.

[94] ACKERSTAFF 97 also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\nu_\mu^*} > 77.1$ GeV.

[95] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[96] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[97] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.

[98] Limit is independent of μ^* decay mode.

[99] Superseded by ADRIANI 93M.

[100] Superseded by DECAMP 92.

Limits for Excited μ (μ^*) from Single Production

These limits are from $e^+e^- \to \mu^*\mu$ and depend on transition magnetic coupling between μ and μ^*. All limits assume $\mu^* \to \mu\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\mu^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>89	95	ADRIANI 93M	L3	$Z \to \mu\mu^*, \lambda_Z > 0.5$
>88	95	ABREU 92C	DLPH	$Z \to \mu\mu^*, \lambda_Z > 0.5$
>91	95	DECAMP 92	ALEP	$Z \to \mu\mu^*, \lambda_Z > 1$
>87	95	AKRAWY 90I	OPAL	$Z \to \mu\mu^*, \lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	95	[101] ACKERSTAFF 98C	OPAL	$e^+e^- \to \mu\mu^*$
		[102,103] ABREU 97B	DLPH	$e^+e^- \to \mu\mu^*$
		[102,104] ACCIARRI 97G	L3	$e^+e^- \to \mu\mu^*$
		[105] ACKERSTAFF 97	OPAL	$e^+e^- \to \mu\mu^*$
		[106] ABREU 96K	DLPH	$e^+e^- \to \mu\mu^*$
		[107] ACCIARRI 96D	L3	$e^+e^- \to \mu\mu^*$
		[108] ALEXANDER 96Q	OPAL	$e^+e^- \to \mu\mu^*$
		[109] BUSKULIC 96W	ALEP	$e^+e^- \to \mu\mu^*$
>85	95	[110] ADEVA 90F	L3	$Z \to \mu\mu^*, \lambda_Z > 1$
>75	95	[110] ADEVA 90F	L3	$Z \to \mu\mu^*, \lambda_Z > 0.1$
>80	95	[111] DECAMP 90G	ALEP	$e^+e^- \to \mu\mu^*, \lambda_Z=1$
>50	95	ADACHI 89B	TOPZ	$e^+e^- \to \mu\mu^*, \lambda_\gamma=0.7$
>46	95	KIM 89	AMY	$e^+e^- \to \mu\mu^*, \lambda_\gamma=0.2$

[101] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.
[102] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.
[103] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.
[104] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.
[105] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.
[106] ABREU 96K result is from e^+e^- collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.
[107] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.
[108] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.
[109] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.
[110] Superseded by ADRIANI 93M.
[111] Superseded by DECAMP 92.

Indirect Limits for Excited μ (μ^*)

These limits make use of loop effects involving μ^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[112] RENARD 82	THEO	$g-2$ of muon

[112] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited τ (τ^*)

Limits for Excited τ (τ^*) from Pair Production

These limits are obtained from $e^+e^- \to \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of τ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the τ^* coupling is assumed to be of sequential type. All limits assume $\tau^* \to \tau\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>84.6	95	[113] ACKERSTAFF 98C	OPAL	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>79.4	95	[114,115] ABREU 97B	DLPH	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
>77.4	95	[114,116] ABREU 97B	DLPH	$e^+e^- \to \tau^*\tau^*$ Sequential type
>79.3	95	[114] ACCIARRI 97G	L3	$e^+e^- \to \tau^*\tau^*$ Sequential type
>79.1	95	[114,117] ACKERSTAFF 97	OPAL	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
>62.2	95	[118] ABREU 96K	DLPH	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
>64.2	95	[119] ACCIARRI 96D	L3	$e^+e^- \to \tau^*\tau^*$ Sequential type
>65.3	95	[119] ALEXANDER 96Q	OPAL	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
>64.8	95	[119] BUSKULIC 96W	ALEP	$e^+e^- \to \tau^*\tau^*$ Sequential type
>45.6	95	ADRIANI 93M	L3	$Z \to \tau^*\tau^*$
>45.3	95	ABREU 92C	DLPH	$Z \to \tau^*\tau^*$
>29.8	95	[120] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>26.1	95	[121] DECAMP 92	ALEP	$Z \to \tau^*\tau^*$; $\Gamma(Z)$
>46.0	95	DECAMP 92	ALEP	$Z \to \tau^*\tau^*$
>33	95	[121] ABREU 91F	DLPH	$Z \to \tau^*\tau^*$; $\Gamma(Z)$
>45.5	95	[122] ADEVA 90L	L3	$Z \to \tau^*\tau^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \to \tau^*\tau^*$
>41.2	95	[123] DECAMP 90G	ALEP	$e^+e^- \to \tau^*\tau^*$
>29.0	95	ADACHI 89B	TOPZ	$e^+e^- \to \tau^*\tau^*$

[113] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $\tau^* \to \nu W$ decay mode: $m_{\tau^*} > 81.3$ GeV.
[114] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.
[115] ABREU 97B also obtain limit from charged current decay mode $\tau^* \to \nu W$, $m_{\tau^*} > 70.9$ GeV.
[116] ABREU 97B also obtain limit from charged current decay mode $\tau^* \to \nu W$, $m_{\tau^*} > 44.6$ GeV.
[117] ACKERSTAFF 97 also obtain limit from charged current decay mode $\tau^* \to \nu W$, $m_{\nu^*_\tau} > 77.1$ GeV.
[118] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.
[119] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.
[120] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.
[121] Limit is independent of τ^* decay mode.
[122] Superseded by ADRIANI 93M.
[123] Superseded by DECAMP 92.

Limits for Excited τ (τ^*) from Single Production

These limits are from $e^+e^- \to \tau^*\tau$ and depend on transition magnetic coupling between τ and τ^*. All limits assume $\tau^* \to \tau\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\tau^*}$ plane. See the original papers.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>88	95	ADRIANI 93M	L3	$Z \to \tau\tau^*, \lambda_Z > 0.5$
>87	95	ABREU 92C	DLPH	$Z \to \tau\tau^*, \lambda_Z > 0.5$
>90	95	DECAMP 92	ALEP	$Z \to \tau\tau^*, \lambda_Z > 0.18$
>86.5	95	AKRAWY 90I	OPAL	$Z \to \tau\tau^*, \lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	95	[124] ACKERSTAFF 98C	OPAL	$e^+e^- \to \tau\tau^*$
		[125,126] ABREU 97B	DLPH	$e^+e^- \to \tau\tau^*$
		[125,127] ACCIARRI 97G	L3	$e^+e^- \to \tau\tau^*$
		[128] ACKERSTAFF 97	OPAL	$e^+e^- \to \tau\tau^*$
		[129] ABREU 96K	DLPH	$e^+e^- \to \tau\tau^*$
		[130] ACCIARRI 96D	L3	$e^+e^- \to \tau\tau^*$
		[131] ALEXANDER 96Q	OPAL	$e^+e^- \to \tau\tau^*$
		[132] BUSKULIC 96W	ALEP	$e^+e^- \to \tau\tau^*$
>88	95	[133] ADEVA 90L	L3	$Z \to \tau\tau^*, \lambda_Z > 1$
>59	95	[134] DECAMP 90G	ALEP	$Z \to \tau\tau^*, \lambda_Z=1$
>40	95	[135] BARTEL 86	JADE	$e^+e^- \to \tau\tau^*, \lambda_\gamma=1$
>41.4	95	[136] BEHREND 86	CELL	$e^+e^- \to \tau\tau^*, \lambda_\gamma=1$
>40.8	95	[136] BEHREND 86	CELL	$e^+e^- \to \tau\tau^*, \lambda_\gamma=0.7$

[124] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.
[125] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.
[126] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.
[127] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.
[128] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.
[129] ABREU 96K result is from e^+e^- collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.
[130] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.
[131] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.
[132] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.
[133] Superseded by ADRIANI 93M.
[134] Superseded by DECAMP 92.
[135] BARTEL 86 is at $E_{\rm cm}$ = 30–46.78 GeV.
[136] BEHREND 86 limit is at $E_{\rm cm}$ = 33–46.8 GeV.

MASS LIMITS for Excited Neutrino (ν^*)

Limits for Excited ν (ν^*) from Pair Production

These limits are obtained from $e^+e^- \to \nu^*\nu^*$ and thus rely only on the (electroweak) charge of ν^*. Form factor effects are ignored unless noted. The ν^* coupling is assumed to be of sequential type unless otherwise noted. Limits assume $\nu^* \to \nu\gamma$ decay except for the $\Gamma(Z)$ measurement which makes no assumption about decay mode.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>84.9	95	[137] ACKERSTAFF 98C	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>77.6	95	[138,139] ABREU 97B	DLPH	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>64.4	95	[138,140] ABREU 97B	DLPH	$e^+e^- \to \nu^*\nu^*$ Sequential type
>71.2	95	[138,141] ACCIARRI 97G	L3	$e^+e^- \to \nu^*\nu^*$ Sequential type
>77.8	95	[138,142] ACKERSTAFF 97	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>61.4	95	[143,144] ACCIARRI 96D	L3	$e^+e^- \to \nu^*\nu^*$ Sequential type
>65.0	95	[145,146] ALEXANDER 96Q	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>63.6	95	[143] BUSKULIC 96W	ALEP	$e^+e^- \to \nu^*\nu^*$ Sequential type
>43.7	95	[147] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>47	95	[148] DECAMP 92	ALEP	
>42.6	95	[149] DECAMP 92	ALEP	$\Gamma(Z)$
>35.4	95	[150,151] DECAMP 90O	ALEP	$\Gamma(Z)$
>46	95	[151,152] DECAMP 90O	ALEP	

[137] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from charged decay modes: $m_{\nu_e^*} > 84.1$ GeV, $m_{\nu_\mu^*} > 83.9$ GeV, and $m_{\nu_\tau^*} > 79.4$ GeV.

[138] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[139] ABREU 97B also obtain limits from charged current decay modes, $m_{\nu^*} > 56.4$ GeV.

[140] ABREU 97B also obtain limits from charged current decay modes, $m_{\nu^*} > 44.9$ GeV.

[141] ACCIARRI 97G also obtain limits from charged current decay mode $\nu_e^* \rightarrow eW$, $m_{\nu^*} >$ 64.5 GeV.

[142] ACKERSTAFF 97 also obtain limits from charged current decay modes $m_{\nu_e^*} > 78.3$ GeV, $m_{\nu_\mu^*} > 78.9$ GeV, $m_{\nu_\tau^*} > 76.2$ GeV.

[143] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[144] ACCIARRI 96D also obtain limit from $\nu^* \rightarrow eW$ decay mode: $m_{\nu^*} > 57.3$ GeV.

[145] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[146] ALEXANDER 96Q also obtain limits from charged current decay modes: $m_{\nu_e^*} > 66.2$ GeV, $m_{\nu_\mu^*} > 66.5$ GeV, $m_{\nu_\tau^*} > 64.7$ GeV.

[147] BARDADIN-OTWINOWSKA 92 limit is for Dirac ν^*. Based on $\Delta\Gamma(Z)$<36 MeV. The limit is 36.4 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.

[148] Limit is based on $\mathrm{B}(Z \rightarrow \nu^*\overline{\nu}^*)\times\mathrm{B}(\nu^* \rightarrow \nu\gamma)^2 < 5\times10^{-5}$ (95%CL) assuming Dirac ν^*, $\mathrm{B}(\nu^* \rightarrow \nu\gamma) = 1$.

[149] Limit is for Dirac ν^*. The limit is 34.6 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.

[150] DECAMP 90O limit is from excess $\Delta\Gamma(Z) < 89$ MeV. The above value is for Dirac ν^*; 26.6 GeV for Majorana ν^*; 44.8 GeV for homodoublet ν^*.

[151] Superseded by DECAMP 92.

[152] DECAMP 90O limit based on $\mathrm{B}(Z \rightarrow \nu^*\nu^*)\cdot\mathrm{B}(\nu^* \rightarrow \nu\gamma)^2 < 7\times10^{-5}$ (95%CL), assuming Dirac ν^*, $\mathrm{B}(\nu^* \rightarrow \nu\gamma) = 1$.

Limits for Excited ν (ν^*) from Single Production

These limits are from $Z \rightarrow \nu\nu^*$ or $ep \rightarrow \nu^*X$ and depend on transition magnetic coupling between ν/e and ν^*. Assumptions about ν^* decay mode are given in footnotes.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
none 40–96	95	[153] BREITWEG	97C	ZEUS	$ep \rightarrow \nu^*X$
>91	95	ADRIANI	93M	L3	$\lambda_Z >1$, $\nu^* \rightarrow \nu\gamma$
>89	95	ADRIANI	93M	L3	$\lambda_Z >1$, $\nu_e^* \rightarrow eW$
>91	95	[154] DECAMP	92	ALEP	$\lambda_Z >1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	95	[155] ACKERSTAFF	98C	OPAL	$ep \rightarrow \nu^*\nu^*$
		[156,157] ABREU	97B	DLPH	$e^+e^- \rightarrow \nu\nu^*$
		[158] ABREU	97I	DLPH	$\nu^* \rightarrow \ell W, \nu Z$
		[159] ABREU	97J	DLPH	$\nu^* \rightarrow \nu\gamma$
		[156,160] ACCIARRI	97G	L3	$e^+e^- \rightarrow \nu\nu^*$
		[161] ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow \nu\nu^*$
		[162] ADLOFF	97	H1	Lepton-flavor violation
		[163] ACCIARRI	96D	L3	$e^+e^- \rightarrow \nu\nu^*$
		[164] ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow \nu\nu^*$
		[165] BUSKULIC	96W	ALEP	$e^+e^- \rightarrow \nu\nu^*$
		[166] DERRICK	95B	ZEUS	$ep \rightarrow \nu^*X$
		[167] ABT	93	H1	$ep \rightarrow \nu^*X$
>87	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu_e^* \rightarrow eW$
		[168] BARDADIN-...	92	RVUE	
>74	95	[154] DECAMP	92	ALEP	$\lambda_Z > 0.034$
>91	95	[169,170] ADEVA	90O	L3	$\lambda_Z >1$
>83	95	[170] ADEVA	90O	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	[170] ADEVA	90O	L3	$\lambda_Z > 0.1$, $\nu_e^* \rightarrow eW$
>90	95	[171,172] DECAMP	90O	ALEP	$\lambda_Z >1$
>74.7	95	[171,172] DECAMP	90O	ALEP	$\lambda_Z > 0.06$

[153] BREITWEG 97C search for single ν^* production in ep collisions with the decay $\nu^* \rightarrow \nu\gamma$. $f=-f'=2\Lambda/m_{\nu^*}$ is assumed for the ν^* coupling. See their Fig. 10 for the exclusion plot in the mass-coupling plane.

[154] DECAMP 92 limit is based on $\mathrm{B}(Z \rightarrow \nu^*\overline{\nu})\times\mathrm{B}(\nu^* \rightarrow \nu\gamma) < 2.7\times10^{-5}$ (95%CL) assuming Dirac ν^*, $\mathrm{B}(\nu^* \rightarrow \nu\gamma) = 1$.

[155] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[156] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[157] See Fig. 4b and Fig. 5b of ABREU 97B for the exclusion limit in the mass-coupling plane.

[158] ABREU 97I limit is from $Z \rightarrow \nu\nu^*$. See their Fig. 12 for the exclusion limit in the mass-coupling plane.

[159] ABREU 97J limit is from $Z \rightarrow \nu\nu^*$. See their Fig. 5 for the exclusion limit in the mass-coupling plane.

[160] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[161] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV, for homodoublet ν^*. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[162] ADLOFF 97 search for single e^* production in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 4 for the rejection limits on the product of the production cross section and the branching ratio.

[163] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[164] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV for homedoublet ν^*. See their Fig. 3b and Fig. 3c for the exclusion limit in the mass-coupling plane.

[165] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[166] DERRICK 95B search for single ν^* production via $\nu^* eW$ coupling in ep collisions with the decays $\nu^* \rightarrow \nu\gamma, \nu Z, eW$. See their Fig. 14 for the exclusion plot in the $m_{\nu^*}-\lambda\gamma$ plane.

[167] ABT 93 search for single ν^* production via $\nu^* eW$ coupling in ep collisions with the decays $\nu^* \rightarrow \nu\gamma, \nu Z, eW$. See their Fig. 4 for exclusion plot in the $m_{\nu^*}-\lambda_W$ plane.

[168] See Fig. 5 of BARDADIN-OTWINOWSKA 92 for combined limit of ADEVA 90O, DECAMP 90O, and DECAMP 92.

[169] Limit is either for $\nu^* \rightarrow \nu\gamma$ or $\nu^* \rightarrow eW$.

[170] Superseded by ADRIANI 93M.

[171] DECAMP 90O limit based on $\mathrm{B}(Z \rightarrow \nu\nu^*)\cdot\mathrm{B}(\nu^* \rightarrow \nu\gamma) < 6\times10^{-5}$ (95%CL), assuming $\mathrm{B}(\nu^* \rightarrow \nu\gamma) = 1$.

[172] Superseded by DECAMP 92.

MASS LIMITS for Excited q (q^*)

Limits for Excited q (q^*) from Pair Production

These limits are obtained from $e^+e^- \rightarrow q^*\overline{q}^*$ and thus rely only on the (electroweak) charge of the q^*. Form factor effects are ignored unless noted. Assumptions about the q^* decay are given in the comments and footnotes.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.6	95	[173] ADRIANI	93M	L3	u or d type, $Z \rightarrow q^*q^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[174] ADRIANI	92F	L3	$Z \rightarrow q^*q^*$
>41.7	95	[175] BARDADIN-...	92	RVUE	u-type, $\Gamma(Z)$
>44.7	95	[175] BARDADIN-...	92	RVUE	d-type, $\Gamma(Z)$
>40.6	95	[176] DECAMP	92	ALEP	u-type, $\Gamma(Z)$
>44.2	95	[176] DECAMP	92	ALEP	d-type, $\Gamma(Z)$
>45	95	[177] DECAMP	92	ALEP	u or d type, $Z \rightarrow q^*q^*$
>45	95	[176] ABREU	91F	DLPH	u-type, $\Gamma(Z)$
>45	95	[176] ABREU	91F	DLPH	d-type, $\Gamma(Z)$
>21.1	95	[178] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow qg$
>22.3	95	[178] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow qg$
>22.5	95	[178] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow q\gamma$
>23.2	95	[178] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow q\gamma$

[173] ADRIANI 93M limit is valid for $\mathrm{B}(q^* \rightarrow qg)> 0.25$ (0.17) for up (down) type.

[174] ADRIANI 92F search for $Z \rightarrow q^*\overline{q}^*$ followed with $q^* \rightarrow q\gamma$ decays and give the limit $\sigma_Z \cdot \mathrm{B}(Z \rightarrow q^*\overline{q}^*) \cdot \mathrm{B}^2(q^* \rightarrow q\gamma) <2$ pb at 95%CL. Assuming five flavors of degenerate q^* of homodoublet type, $\mathrm{B}(q^* \rightarrow q\gamma) <4\%$ is obtained for $m_{q^*} <45$ GeV.

[175] BARDADIN-OTWINOWSKA 92 limit based on $\Delta\Gamma(Z)$<36 MeV.

[176] These limits are independent of decay modes.

[177] Limit is for $\mathrm{B}(q^* \rightarrow qg)+\mathrm{B}(q^* \rightarrow q\gamma)=1$.

[178] BEHREND 86C search for $e^+e^- \rightarrow q^*\overline{q}^*$ for $m_{q^*} >5$ GeV. But $m < 5$ GeV excluded by total hadronic cross section. The limits are for point-like photon couplings of excited quarks.

Limits for Excited q (q^*) from Single Production

These limits are from $e^+e^- \rightarrow q^*\overline{q}$ or $p\overline{p} \rightarrow q^*X$ and depend on transition magnetic couplings between q and q^*. Assumptions about q^* decay mode are given in the footnotes and comments.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>570 (CL = 95%) OUR EVALUATION					
none 200–520 and 580–760	95	[179] ABE	97G	CDF	$p\overline{p} \rightarrow q^*X$, $q^* \rightarrow 2$ jets
none 40–169	95	[180] BREITWEG	97C	ZEUS	$ep \rightarrow q^*X$
none 80–570	95	[181] ABE	95N	CDF	$p\overline{p} \rightarrow q^*X$, $q^* \rightarrow qg$ $q\gamma$, qW
>288	90	[182] ALITTI	93	UA2	$p\overline{p} \rightarrow q^*X$, $q^* \rightarrow qg$
> 88	95	[183] DECAMP	92	ALEP	$Z \rightarrow qq^*$, $\lambda_Z >1$
> 86	95	[183] AKRAWY	90J	OPAL	$Z \rightarrow qq^*$, $\lambda_Z > 1.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[184] ADLOFF	97	H1	Lepton-flavor violation
		[185] DERRICK	95B	ZEUS	$ep \rightarrow q^*X$
none 80–540	95	[186] ABE	94	CDF	$p\overline{p} \rightarrow q^*X$, $q^* \rightarrow q\gamma$, qW
> 79	95	[187] ADRIANI	93M	L3	λ_Z(L3)> 0.06
		[188] ABREU	92D	DLPH	$Z \rightarrow qq^*$
		[189] ADRIANI	92F	L3	$Z \rightarrow qq^*$
> 75	95	[187] DECAMP	92	ALEP	$Z \rightarrow qq^*$, $\lambda_Z >1$
		[190] ALBAJAR	89	UA1	$p\overline{p} \rightarrow q^*X$, $q^* \rightarrow qW$
> 39	95	[191] BEHREND	86C	CELL	$e^+e^- \rightarrow q^*\overline{q}$ ($q^* \rightarrow qg, q\gamma$), λ_γ=1

[179] ABE 97G search for new particle decaying to dijets.

[180] BREITWEG 97C search for single q^* production in ep collisions with the decays $q^* \rightarrow q\gamma$, qW. f_s=0, and $f=-f'=2\Lambda/m_{q^*}$ is assumed for the q^* coupling. See their Fig. 11 for the exclusion plot in the mass-coupling plane.

[181] ABE 95N assume a degenerate u^* and d^* with $f_s=f=f'=\Lambda/m_{q^*}$. See their Fig. 4 for the excluded region in $m_{q^*} - f$ plane.

[182] ALITTI 93 search for resonances in the two-jet invariant mass. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$. u^* and d^* are assumed to be degenerate. If not, the limit for u^* (d^*) is 277 (247) GeV if $m_{d^*} \gg m_{u^*}$ ($m_{u^*} \gg m_{d^*}$).

[183] Assumes B($q^* \to q\gamma$) = 0.1.

[184] ADLOFF 97 search for single q^* production in ep collisions with the decay $q^* \to q\gamma$. See their Fig. 6 for the rejection limits on the product of the production cross section and the branching ratio.

[185] DERRICK 95B search for single q^* production via $q^* q \gamma$ coupling in ep collisions with the decays $q^* \to qW$, qZ, qg, $q\gamma$. See their Fig. 15 for the exclusion plot in the $m_{q^*}-\lambda\gamma$ plane.

[186] ABE 94 search for resonances in jet-γ and jet-W invariant mass in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$ and u^* and d^* are assumed to be degenerate. See their Fig. 4 for the excluded region in m_{q^*}-f plane.

[187] Assumes B($q^* \to qg$) = 1.

[188] ABREU 92D give $\sigma(e^+e^- \to Z \to q^*\overline{q}$ or $q\overline{q}^*) \times$B($q^* \to q\gamma$) <15 pb (95% CL) for m_{q^*} <80 GeV.

[189] ADRIANI 92F search for $Z \to qq^*$ with $q^* \to q\gamma$ and give the limit $\sigma_Z \cdot$ B($Z \to qq^*$) $\cdot$ B($q^* \to q\gamma$) <(2–10) pb (95%CL) for m_{q^*} = (46–82) GeV.

[190] ALBAJAR 89 give $\sigma(q^* \to W+\text{jet})/\sigma(W) < 0.019$ (90% CL) for $m_{q^*} > 220$ GeV.

[191] BEHREND 86C has E_{cm} = 42.5–46.8 GeV. See their Fig. 3 for excluded region in the $m_{q^*}-(\lambda_\gamma/m_{q^*})^2$ plane. The limit is for $\lambda_\gamma = 1$ with $\eta_L = \eta_R = 1$.

MASS LIMITS for Color Sextet Quarks (q_6)

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>84	95	[192] ABE	89D	CDF	$p\overline{p} \to q_6\overline{q}_6$

[192] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color sextet quark is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. A limit of 121 GeV is obtained for a color decuplet.

MASS LIMITS for Color Octet Charged Leptons (ℓ_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>86	95	[193] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \to \ell_8\overline{\ell}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[194] ABT	93	H1	e_8: $ep \to e_8X$
none 3.0–30.3	95	[195] KIM	90	AMY	e_8: $e^+e^- \to ee +$ jets
none 3.5–30.3	95	[195] KIM	90	AMY	μ_8: $e^+e^- \to \mu\mu +$ jets
		[196] KIM	90	AMY	e_8: $e^+e^- \to gg$; R
>19.8	95	[197] BARTEL	87B	JADE	e_8, μ_8, τ_8: e^+e^-; R
none 5–23.2	95	[197] BARTEL	87B	JADE	μ_8: $e^+e^- \to \mu\mu +$ jets
		[198] BARTEL	85K	JADE	e_8: $e^+e^- \to gg$; R

[193] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color octet lepton is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. The limit improves to 99 GeV if it always fragments into a unit-charged hadron.

[194] ABT 93 search for e_8 production via e-gluon fusion in ep collisions with $e_8 \to eg$. See their Fig. 3 for exclusion plot in the m_{e_8}–Λ plane for m_{e_8} = 35–220 GeV.

[195] KIM 90 is at E_{cm} = 50–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[196] KIM 90 result $(m_{e_8}\Lambda_M)^{1/2} >$ 178.4 GeV (95%CL, $\alpha_s = 0.16$ used) is subject to the same restriction as for BARTEL 85K.

[197] BARTEL 87B is at E_{cm} = 46.3–46.78 GeV. The limits assume ℓ_8 pair production cross sections to be eight times larger than those of the corresponding heavy lepton pair production.

[198] In BARTEL 85K, R can be affected by $e^+e^- \to gg$ via e_q exchange. Their limit m_{e_8} >173 GeV (CL=95%) at $\lambda = m_{e_8}/\Lambda_M = 1$ ($\eta_L = \eta_R = 1$) is not listed above because the cross section is sensitive to the product $\eta_L\eta_R$, which should be absent in ordinary theory with electronic chiral invariance.

MASS LIMITS for Color Octet Neutrinos (ν_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>110	90	[199] BARGER	89	RVUE	ν_8: $p\overline{p} \to \nu_8\overline{\nu}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 3.8–29.8	95	[200] KIM	90	AMY	ν_8: $e^+e^- \to$ acoplanar jets
none 9–21.9	95	[201] BARTEL	87B	JADE	ν_8: $e^+e^- \to$ acoplanar jets

[199] BARGER 89 used ABE 89B limit for events with large missing transverse momentum. Two-body decay $\nu_8 \to \nu g$ is assumed.

[200] KIM 90 is at E_{cm} = 50–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[201] BARTEL 87B is at E_{cm} = 46.3–46.78 GeV. The limit assumes the ν_8 pair production cross section to be eight times larger than that of the corresponding heavy neutrino pair production. This assumption is not valid in general for the weak couplings, and the limit can be sensitive to its $SU(2)_L \times U(1)_Y$ quantum numbers.

MASS LIMITS for W_8 (Color Octet W Boson)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[202] ALBAJAR	89	UA1	$p\overline{p} \to W_8X$, $W_8 \to Wg$

[202] ALBAJAR 89 give $\sigma(W_8 \to W+\text{jet})/\sigma(W) < 0.019$ (90% CL) for $m_{W_8} > 220$ GeV.

Limits on $ZZ\gamma$ Coupling

Limits are for the electric dipole transition form factor for $Z \to \gamma Z^*$ parametrized as $f(s') = \beta(s'/m_Z^2-1)$, where s' is the virtual Z mass. In the Standard Model $\beta \sim 10^{-5}$.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.80	95	ADRIANI	92J	L3	$Z \to \gamma\nu\overline{\nu}$

REFERENCES FOR Searches for Quark and Lepton Compositeness

ACKERSTAFF	98	EPJ C1 21	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98C	EPJ C1 45	K. Ackerstaff+	(OPAL Collab.)
ABE	97G	PR D55 R5263	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABE	97T	PRL 79 2198	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABREU	97B	PL B393 245	+Adam, Adye, Ajinenko, Alekseev+	(DELPHI Collab.)
ABREU	97I	ZPHY C74 57	+Adam, Adye, Ajinenko, Alekseev+	(DELPHI Collab.)
Also	97L	ZPHY C75 580 erratum	Abreu, Adam, Adye, Ajinenko+	(DELPHI Collab.)
ABREU	97J	ZPHY C74 577	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97G	PL B401 139	+Adriani, Aguilar-Benitez, Ahlen, Alpat+	(L3 Collab.)
ACKERSTAFF	97	PL B391 197	+Alexander, Allison, Altekamp, Ametewee+	(OPAL Collab.)
ACKERSTAFF	97C	PL B391 221	+Alexander, Allison, Altekamp, Ametewee+	(OPAL Collab.)
ADLOFF	97	NP B483 44	+Aid, Anderson, Andreev, Andrieu, Arndt+	(H1 Collab.)
ARIMA	97	PR D55 19	+Odaka, Ogawa, Shirai, Tsuboyama+	(VENUS Collab.)
BREITWEG	97C	ZPHY C76 631	+Derrick, Krakauer, Magill+	(ZEUS Collab.)
DEANDREA	97	PL B409 277		(MARS)
ABE	96	PRL 77 438	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96S	PRL 77 5336	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABREU	96K	PL B380 480	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	96D	PL B370 211	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	96L	PL B384 323	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ALEXANDER	96K	PL B377 222	+	(OPAL Collab.)
ALEXANDER	96Q	PL B386 463	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96W	PL B385 445	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
BUSKULIC	96Z	PL B384 333	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABE	95N	PRL 74 3538	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ACCIARRI	95G	PL B353 136	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AID	95	PL B353 578	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
DERRICK	95B	ZPHY C65 627	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	94	PRL 72 3004	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
DIAZCRUZ	94	PR D49 R2149	Diaz Cruz, Sampayo	(CINV)
VELISSARIS	94	PL B331 227	+Lusin, Chung, Park, Cho, Bodek, Kim+	(AMY Collab.)
ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ABT	93	NP B396 3	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALITTI	93	NP B400 3	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BUSKULIC	93Q	ZPHY C59 215	+Decamp, Goy, Lees, Minard, Mours+	(ALEPH Collab.)
DERRICK	93B	PL B316 207	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	92B	PRL 68 1463	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92D	PRL 68 1104	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92M	PRL 69 2896	+Amidei, Anway-Wiese, Apollinari, Atac+	(CDF Collab.)
ABREU	92C	ZPHY C53 41	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADRIANI	92B	PL B288 404	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92J	PL B297 469	+Aguilar-Benitez, Ahlen, Alcarez, Aloisio+	(L3 Collab.)
BARDADIN-...	92	ZPHY C55 163	Bardadin-Otwinowska	(CLER)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
HOWELL	92	PL B291 206	+Koltick, Tauchi, Miyamoto, Kichimi+	(TOPAZ Collab.)
KROHA	92	PR D46 58		(ROCH)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
SHIMOZAWA	92	PL B284 144	+Fujimoto, Abe, Adachi, Doser+	(TOPAZ Collab.)
ABE	91D	PRL 67 2418	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91E	PL B268 296	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALITTI	91B	PL B257 232	+Ansari, Autiero, Bareyre, Blaylock+	(UA2 Collab.)
BEHREND	91B	ZPHY C51 143	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
BEHREND	91C	ZPHY C51 149	+Criegee, Field, Franke, Jung, Meyer+	(CELLO Collab.)
Also	91B	ZPHY C51 143	Behrend, Criegee, Field, Franke, Jung+	(CELLO Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADEVA	90F	PL B247 177	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90K	PL B250 199	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
ADEVA	90L	PL B250 205	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90O	PL B252 525	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90F	PL B241 133	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90I	PL B244 135	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90G	PL B236 501	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90O	PL B250 172	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
KIM	90	PL B240 243	+Breedon, Ko, Lander, Maeshima, Malchow+	(AMY Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89B	PRL 62 1825	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89D	PRL 63 1447	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89H	PRL 62 3020	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89J	ZPHY C45 175	+Amako, Arai, Fukawa+	(VENUS Collab.)
ABE	89L	PL B232 425	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADACHI	89B	PL B228 553	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BARGER	89	PL B220 464	+Hagiwara, Han, Zeppenfeld	(WISC, KEK)
BEHREND	89B	PL B222 163	+Criegee, Dainton, Field, Franke+	(CELLO Collab.)
BRAUNSCH...	89C	ZPHY C43 549	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
HAGIWARA	89	PL B219 369	+Sakuda, Terunuma	(KEK, DURH, HIRO)
KIM	89	PL B223 476	+Kim, Kang, Lee, Myung, Bacala	(AMY Collab.)
ABE	88B	PL B213 400	+Amako, Arai, Asano, Chiba, Chiba+	(VENUS Collab.)
BARINGER	88	PL B206 551	+Bylsma, De Bonte, Koltick, Low+	(HRS Collab.)
BRAUNSCH...	88	ZPHY C37 171	Braunschweig, Gerhards+	(TASSO Collab.)

BRAUNSCH...	88D	ZPHY C40 163	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	+Becker, Felst+	(JADE Collab.)
BEHREND	87C	PL B191 209	+Buerger, Criegee, Dainton+	(CELLO Collab.)
FERNANDEZ	87B	PR D35 10	+Ford, Qi, Read, Smith, Camporesi+	(MAC Collab.)
ARNISON	86C	PL B172 461	+Albrow, Allkofer+	(UA1 Collab.)
ARNISON	86D	PL B177 244	+Albajar, Albrow+	(UA1 Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
BEHREND	86	PL 168B 420	+Buerger, Criegee, Fenner+	(CELLO Collab.)
BEHREND	86C	PL B181 178	+Buerger, Criegee, Dainton+	(CELLO Collab.)
DERRICK	86	PL 166B 463	+Gan, Kooijman, Loos+	(HRS Collab.)
Also	86B	PR D34 3286	Derrick, Gan, Kooijman, Loos, Musgrave+	(HRS Collab.)
DERRICK	86B	PR D34 3286	+Gan, Kooijman, Loos, Musgrave+	(HRS Collab.)
GRIFOLS	86	PL 168B 264	+Peris	(BARC)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
APPEL	85	PL 160B 349	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	85K	PL 160B 337	+Becker, Cords, Eichler+	(JADE Collab.)
BERGER	85	ZPHY C28 1	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BERGER	85B	ZPHY C27 341	+Deuter, Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BAGNAIA	84C	PL 138B 430	+Banner, Battiston+	(UA2 Collab.)
BARTEL	84D	PL 146B 437	+Becker, Bowdery, Cords+	(JADE Collab.)
BARTEL	84E	PL 146B 121	+Becker, Bowdery, Cords, Felst+	(JADE Collab.)
EICHTEN	84	RMP 56 579	+Hinchliffe, Lane, Quigg	(FNAL, LBL, OSU)
ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
RENARD	82	PL 116B 264		(CERN)

WIMPs and Other Particle Searches

OMITTED FROM SUMMARY TABLE

WIMPS AND OTHER PARTICLE SEARCHES

Revised October 1997 by K. Hikasa (Tohoku University).

We collect here those searches which do not appear in any of the above search categories. These are listed in the following order:

1. Galactic WIMP (weakly-interacting massive particle) searches
2. Concentration of stable particles in matter
3. Limits on neutral particle production at accelerators
4. Limits on jet-jet resonance in hadron collisions
5. Limits on charged particles in e^+e^- collisions
6. Limits on charged particles in hadron reactions
7. Limits on charged particles in cosmic rays

Note that searches appear in separate sections elsewhere for Higgs bosons (and technipions), other heavy bosons (including W_R, W', Z', leptoquarks, axigluons), axions (including pseudo-Goldstone bosons, Majorons, familons), heavy leptons, heavy neutrinos, free quarks, monopoles, supersymmetric particles, and compositeness. We include specific WIMP searches in the appropriate sections when they yield limits on hypothetical particles such as supersymmetric particles, axions, massive neutrinos, monopoles, *etc.*

We omit papers on CHAMP's, millicharged particles, and other exotic particles. We no longer list for limits on tachyons and centauros. See our 1994 edition for these limits.

GALACTIC WIMP SEARCHES

Cross-Section Limits for Dark Matter Particles (X^0) on Nuclei

These limits are for weakly-interacting stable particles that may constitute the invisible mass in the galaxy. Unless otherwise noted, a local mass density of 0.3 GeV/cm^3 is assumed; see each paper for velocity distribution assumptions. In the papers the limit is given as a function of the X^0 mass. Here we list limits only for typical mass values of 20 GeV, 100 GeV, and 1 TeV. Specific limits on supersymmetric dark matter particles may be found in the Supersymmetry section.

For m_{X^0} = 20 GeV

VALUE (nb)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[1] BERNABEI 97	CNTR	F
< 0.8		ALESSAND... 96	CNTR	O
< 6		ALESSAND... 96	CNTR	Te
< 0.02	90	[2] BELLI 96	CNTR	^{129}Xe, inel.
		[3] BELLI 96C	CNTR	^{129}Xe
< 0.004	90	[4] BERNABEI 96	CNTR	Na
< 0.3	90	[4] BERNABEI 96	CNTR	I
< 0.2	95	[5] SARSA 96	CNTR	Na
< 0.015	90	[6] SMITH 96	CNTR	Na
< 0.05	95	[7] GARCIA 95	CNTR	Natural Ge
< 0.1	95	QUENBY 95	CNTR	Na
< 90	90	[8] SNOWDEN-... 95	MICA	^{16}O
$< 4 \times 10^3$	90	[8] SNOWDEN-... 95	MICA	^{39}K
< 0.7	90	BACCI 92	CNTR	Na
< 0.12	90	[9] REUSSER 91	CNTR	Natural Ge
< 0.06	95	CALDWELL 88	CNTR	Natural Ge

[1] BERNABEI 97 give $\sigma < 12$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[2] BELLI 96 limit for inelastic scattering $X^0\ ^{129}\mathrm{Xe} \rightarrow X^0\ ^{129}\mathrm{Xe}^*$(39.58 keV).

[3] BELLI 96C use background subtraction and obtain $\sigma < 150$ pb (< 1.5 fb) (?%CL) for spin-dependent (independent) X^0-proton cross section.

[4] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[5] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[6] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[7] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[8] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[9] REUSSER 91 limit here is changed from published (0.04) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For m_{X^0} = 100 GeV

VALUE (nb)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[10] BERNABEI 97	CNTR	F
< 4		ALESSAND... 96	CNTR	O
< 25		ALESSAND... 96	CNTR	Te
< 0.006	90	[11] BELLI 96	CNTR	^{129}Xe, inel.
		[12] BELLI 96C	CNTR	^{129}Xe
< 0.001	90	[13] BERNABEI 96	CNTR	Na
< 0.3	90	[13] BERNABEI 96	CNTR	I
< 0.7	95	[14] SARSA 96	CNTR	Na
< 0.03	90	[15] SMITH 96	CNTR	Na
< 0.8	90	[15] SMITH 96	CNTR	I
< 0.35	95	[16] GARCIA 95	CNTR	Natural Ge
< 0.6	95	QUENBY 95	CNTR	Na
< 3	95	QUENBY 95	CNTR	I
$< 1.5 \times 10^2$	90	[17] SNOWDEN-... 95	MICA	^{16}O
$< 4 \times 10^2$	90	[17] SNOWDEN-... 95	MICA	^{39}K
< 0.08	90	[18] BECK 94	CNTR	^{76}Ge
< 2.5	90	BACCI 92	CNTR	Na
< 3	90	BACCI 92	CNTR	I
< 0.9	90	[19] REUSSER 91	CNTR	Natural Ge
< 0.7	95	CALDWELL 88	CNTR	Natural Ge

[10] BERNABEI 97 give $\sigma < 5$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[11] BELLI 96 limit for inelastic scattering $X^0\ ^{129}\mathrm{Xe} \rightarrow X^0\ ^{129}\mathrm{Xe}^*$(39.58 keV).

[12] BELLI 96C use background subtraction and obtain $\sigma < 0.35$ pb (< 0.15 fb) (?%CL) for spin-dependent (independent) X^0-proton cross section.

[13] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[14] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[15] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[16] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[17] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[18] BECK 94 uses enriched ^{76}Ge (86% purity).

[19] REUSSER 91 limit here is changed from published (0.3) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For m_{X^0} = 1 TeV

VALUE (nb)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[20] BERNABEI 97	CNTR	F
< 40		ALESSAND... 96	CNTR	O
< 700		ALESSAND... 96	CNTR	Te
< 0.05	90	[21] BELLI 96	CNTR	^{129}Xe, inel.
< 1.5	90	[22] BELLI 96	CNTR	^{129}Xe, inel.
		[23] BELLI 96C	CNTR	^{129}Xe
< 0.01	90	[24] BERNABEI 96	CNTR	Na
< 9	90	[24] BERNABEI 96	CNTR	I
< 7	95	[25] SARSA 96	CNTR	Na
< 0.3	90	[26] SMITH 96	CNTR	Na

< 6	90	[26] SMITH 96	CNTR	I
< 6	95	[27] GARCIA 95	CNTR	Natural Ge
< 8	95	QUENBY 95	CNTR	Na
< 50	95	QUENBY 95	CNTR	I
$< 7 \times 10^2$	90	[28] SNOWDEN-... 95	MICA	^{16}O
$< 1 \times 10^3$	90	[28] SNOWDEN-... 95	MICA	^{39}K
< 0.8	90	[29] BECK 94	CNTR	^{76}Ge
< 30	90	BACCI 92	CNTR	Na
< 30	90	BACCI 92	CNTR	I
< 15	90	[30] REUSSER 91	CNTR	Natural Ge
< 6	95	CALDWELL 88	CNTR	Natural Ge

[20] BERNABEI 97 give $\sigma < 32$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[21] BELLI 96 limit for inelastic scattering $X^0\ {}^{129}\text{Xe} \rightarrow X^0\ {}^{129}\text{Xe}^*$(39.58 keV).

[22] BELLI 96 limit for inelastic scattering $X^0\ {}^{129}\text{Xe} \rightarrow X^0\ {}^{129}\text{Xe}^*$(236.14 keV).

[23] BELLI 96C use background subtraction and obtain $\sigma < 0.7$ pb (< 0.7 fb) (?%CL) for spin-dependent (independent) X^0-proton cross section.

[24] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[25] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[26] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[27] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[28] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[29] BECK 94 uses enriched ^{76}Ge (86% purity).

[30] REUSSER 91 limit here is changed from published (5) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

CONCENTRATION OF STABLE PARTICLES IN MATTER

Concentration of Heavy (Charge +1) Stable Particles in Matter

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<4 \times 10^{-17}$	95	[31] YAMAGATA 93	SPEC	Deep sea water, m=5–1600m_p
$<6 \times 10^{-15}$	95	[32] VERKERK 92	SPEC	Water, $m = 10^5$ to 3×10^7 GeV
$<7 \times 10^{-15}$	95	[32] VERKERK 92	SPEC	Water, $m = 10^4$, 6×10^7 GeV
$<9 \times 10^{-15}$	95	[32] VERKERK 92	SPEC	Water, $m = 10^8$ GeV
$<3 \times 10^{-23}$	90	[33] HEMMICK 90	SPEC	Water, $m = 1000m_p$
$<2 \times 10^{-21}$	90	[33] HEMMICK 90	SPEC	Water, $m = 5000m_p$
$<3 \times 10^{-20}$	90	[33] HEMMICK 90	SPEC	Water, $m = 10000m_p$
$<1. \times 10^{-29}$		SMITH 82B	SPEC	Water, m=30–400m_p
$<2. \times 10^{-28}$		SMITH 82B	SPEC	Water, m=12–1000m_p
$<1. \times 10^{-14}$		SMITH 82B	SPEC	Water, m >1000 m_p
$<(0.2\text{–}1.) \times 10^{-21}$		SMITH 79	SPEC	Water, m=6–350 m_p

[31] YAMAGATA 93 used deep sea water at 4000 m since the concentration is enhanced in deep sea due to gravity.

[32] VERKERK 92 looked for heavy isotopes in sea water and put a bound on concentration of stable charged massive particle in sea water. The above bound can be translated into into a bound on charged dark matter particle (5×10^6 GeV), assuming the local density, ρ=0.3 GeV/cm^3, and the mean velocity $\langle v \rangle$=300 km/s.

[33] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.

Concentration of Heavy (Charge −1) Stable Particles

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<4 \times 10^{-20}$	90	[34] HEMMICK 90	SPEC	C, $M = 100m_p$
$<8 \times 10^{-20}$	90	[34] HEMMICK 90	SPEC	C, $M = 1000m_p$
$<2 \times 10^{-16}$	90	[34] HEMMICK 90	SPEC	C, $M = 10000m_p$
$<6 \times 10^{-13}$	90	[34] HEMMICK 90	SPEC	Li, $M = 1000m_p$
$<1 \times 10^{-11}$	90	[34] HEMMICK 90	SPEC	Be, $M = 1000m_p$
$<6 \times 10^{-14}$	90	[34] HEMMICK 90	SPEC	B, $M = 1000m_p$
$<4 \times 10^{-17}$	90	[34] HEMMICK 90	SPEC	O, $M = 1000m_p$
$<4 \times 10^{-15}$	90	[34] HEMMICK 90	SPEC	F, $M = 1000m_p$
$< 1.5 \times 10^{-13}$/nucleon	68	[35] NORMAN 89	SPEC	$^{206}\text{Pb}X^-$
$< 1.2 \times 10^{-12}$/nucleon	68	[35] NORMAN 87	SPEC	$^{56,58}\text{Fe}X^-$

[34] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.

[35] Bound valid up to $m_{X^-} \sim 100$ TeV.

LIMITS ON NEUTRAL PARTICLE PRODUCTION

Production Cross Section of Radiatively-Decaying Neutral Particle

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (pb)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<(2.5–0.5)	95	[36] ACKERSTAFF 97B	OPAL	$e^+e^- \rightarrow X^0 Y^0$, $X^0 \rightarrow Y^0 \gamma$
<(1.6–0.9)	95	[37] ACKERSTAFF 97B	OPAL	$e^+e^- \rightarrow X^0 X^0$, $X^0 \rightarrow Y^0 \gamma$

[36] ACKERSTAFF 97B associated production limit is for m_{X^0} = 80–160 GeV, m_{Y^0}=0 from 10.0 pb^{-1} at $\sqrt{s} = 161$ GeV. See their Fig. 3(a).

[37] ACKERSTAFF 97B pair production limit is for m_{X^0} = 40–80 GeV, m_{Y^0}=0 from 10.0 pb^{-1} at $\sqrt{s} = 161$ GeV. See their Fig. 3(b).

Heavy Particle Production Cross Section

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (cm^2/*N*)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$< 10^{-36}\text{–}10^{-33}$	90		[38] GALLAS 95	TOF	m= 0.5–20 GeV
$<(4\text{–}0.3) \times 10^{-31}$	95		[39] AKESSON 91	CNTR	m = 0–5 GeV
$<2 \times 10^{-36}$	90	0	[40] BADIER 86	BDMP	$\tau = (0.05\text{–}1.) \times 10^{-8}$s
$<2.5 \times 10^{-35}$		0	[41] GUSTAFSON 76	CNTR	$\tau > 10^{-7}$ s

[38] GALLAS 95 limit is for a weakly interacting neutral particle produced in 800 GeV/c pN interactions decaying with a lifetime of 10^{-4}–10^{-8} s. See their Figs. 8 and 9. Similar limits are obtained for a stable particle with interaction cross section 10^{-29}–10^{-33} cm^2. See Fig. 10.

[39] AKESSON 91 limit is from weakly interacting neutral long-lived particles produced in pN reaction at 450 GeV/c performed at CERN SPS. Bourquin-Gaillard formula is used as the production model. The above limit is for $\tau > 10^{-7}$ s. For $\tau > 10^{-9}$ s, $\sigma < 10^{-30}$ cm^{-2}/nucleon is obtained.

[40] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.

[41] GUSTAFSON 76 is a 300 GeV FNAL experiment looking for heavy (m >2 GeV) long-lived neutral hadrons in the M4 neutral beam. The above typical value is for m = 3 GeV and assumes an interaction cross section of 1 mb. Values as a function of mass and interaction cross section are given in figure 2.

Production of New Penetrating Non-ν Like States in Beam Dump

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
	[42] LOSECCO 81	CALO	28 GeV protons

[42] No excess neutral-current events leads to σ(production) × σ(interaction)×acceptance $< 2.26 \times 10^{-71}$ cm^4/nucleon^2 (CL = 90%) for light neutrals. Acceptance depends on models (0.1 to $4. \times 10^{-4}$).

LIMITS ON JET-JET RESONANCES

Heavy Particle Production Cross Section in $p\overline{p}$

Limits are for a particle decaying to two hadronic jets.

• • • We do not use the following data for averages, fits, limits, etc. • • •

Units(pb)	*CL%*	*Mass(GeV)*	*DOCUMENT ID*	*TECN*	*COMMENT*
			[43] ABE 97G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2 jets
<2603	95	200	[44] ABE 93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 44	95	400	[44] ABE 93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 7	95	600	[44] ABE 93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets

[43] ABE 97G search for narrow dijet resonances in $p\overline{p}$ collisions with 106 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV. Limits on $\sigma(p\overline{p} \rightarrow X + \text{anything}) \cdot B(X \rightarrow JJ)$ in the range 10^4–10^{-1} pb (95%CL) are given for dijet mass m=200–1150 GeV with both jets having $|\eta| < 2.0$ and the dijet system having $|\cos\theta^*| < 0.67$. See their Table I for the list of limits. Supersedes ABE 93G.

[44] ABE 93G gives cross section times branching ratio into light (d, u, s, c, b) quarks for $\Gamma = 0.02\ M$. Their Table II gives limits for M = 200–900 GeV and $\Gamma = (0.02\text{–}0.2)\ M$.

LIMITS ON CHARGED PARTICLES IN e^+e^-

Heavy Particle Production Cross Section in e^+e^-

Ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ unless noted. See also entries in Free Quark Search and Magnetic Monopole Searches.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
			[45] ABREU 97D	DLPH	Q=1,2/3, m=45–84 GeV
			[46] BARATE 97K	ALEP	Q=1, m=45–85 GeV
$<2 \times 10^{-5}$	95		[47] AKERS 95R	OPAL	Q=1, m= 5–45 GeV
$<1 \times 10^{-5}$	95		[47] AKERS 95R	OPAL	Q=2, m= 5–45 GeV
$<2 \times 10^{-3}$	90		[48] BUSKULIC 93C	ALEP	Q=1, m=32–72 GeV
$<(10^{-2}\text{–}1)$	95		[49] ADACHI 90C	TOPZ	Q = 1, m= 1–16, 18–27 GeV
$<7 \times 10^{-2}$	90		[50] ADACHI 90E	TOPZ	Q = 1, m = 5–25 GeV
$<1.6 \times 10^{-2}$	95	0	[51] KINOSHITA 82	PLAS	Q=3–180, m <14.5 GeV
$<5.0 \times 10^{-2}$	90	0	[52] BARTEL 80	JADE	Q=(3,4,5)/3 2–12 GeV

[45] ABREU 97D search for pair production of long-lived particles and give limits σ <(0.4–2.3) pb (95%CL) for various center-of-mass energies $\sqrt{s}$=130–136, 161, and 172 GeV, assuming an almost flat production distribution in $\cos\theta$.

[46] BARATE 97K search for pair production of long-lived charged particles at $\sqrt{s} = 130$, 136, 161, and 172 GeV and give limits $\sigma <(0.2$–$0.4)$ pb (95%CL) for spin-0 and spin-1/2 particles with m=45–85 GeV. The limit is translated to the cross section at $\sqrt{s}$=172 GeV with the $\sqrt{s}$ dependence described in the paper. See their Figs. 2 and 3 for limits on $J = 1/2$ and $J = 0$ cases.

[47] AKERS 95R is a CERN-LEP experiment with $W_{cm} \sim m_Z$. The limit is for the production of a stable particle in multihadron events normalized to $\sigma(e^+ e^- \rightarrow$ hadrons). Constant phase space distribution is assumed. See their Fig. 3 for bounds for $Q = \pm 2/3$, $\pm 4/3$.

[48] BUSKULIC 93C is a CERN-LEP experiment with $W_{cm} = m_Z$. The limit is for a pair or single production of heavy particles with unusual ionization loss in TPC. See their Fig. 5 and Table 1.

[49] ADACHI 90C is a KEK-TRISTAN experiment with W_{cm} = 52–60 GeV. The limit is for pair production of a scalar or spin-1/2 particle. See Figs. 3 and 4.

[50] ADACHI 90E is KEK-TRISTAN experiment with W_{cm} = 52–61.4 GeV. The above limit is for inclusive production cross section normalized to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)\cdot\beta(3-\beta^2)/2$, where $\beta = (1 - 4m^2/W^2_{cm})^{1/2}$. See the paper for the assumption about the production mechanism.

[51] KINOSHITA 82 is SLAC PEP experiment at W_{cm} = 29 GeV using lexan and ^{39}Cr plastic sheets sensitive to highly ionizing particles.

[52] BARTEL 80 is DESY-PETRA experiment with W_{cm} = 27–35 GeV. Above limit is for inclusive pair production and ranges between $1. \times 10^{-1}$ and $1. \times 10^{-2}$ depending on mass and production momentum distributions. (See their figures 9, 10, 11).

Branching Fraction of Z^0 to a Pair of Stable Charged Heavy Fermions

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<5 \times 10^{-6}$	95	[53] AKERS	95R	OPAL	m= 40.4–45.6 GeV
$<1 \times 10^{-3}$	95	AKRAWY	90O	OPAL	m = 29–40 GeV

[53] AKERS 95R give the 95% CL limit $\sigma(X\overline{X})/\sigma(\mu\mu) < 1.8\times10^{-4}$ for the pair production of singly- or doubly-charged stable particles. The limit applies for the mass range 40.4–45.6 GeV for $X^{\pm}$ and < 45.6 GeV for $X^{\pm\pm}$. See the paper for bounds for $Q = \pm 2/3$, $\pm 4/3$.

LIMITS ON CHARGED PARTICLES IN HADRONIC REACTIONS

Heavy Particle Production Cross Section

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (nb)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.05	95		[54] ABE	92J	CDF	m=50–200 GeV
<30–130			[55] CARROLL	78	SPEC	m=2–2.5 GeV
<100		0	[56] LEIPUNER	73	CNTR	m=3–11 GeV

[54] ABE 92J look for pair production of unit-charged particles which leave detector before decaying. Limit shown here is for m=50 GeV. See their Fig. 5 for different charges and stronger limits for higher mass.

[55] CARROLL 78 look for neutral, $S = -2$ dihyperon resonance in $pp \rightarrow 2K^+X$. Cross section varies within above limits over mass range and p_{lab} = 5.1–5.9 GeV/c.

[56] LEIPUNER 73 is an NAL 300 GeV p experiment. Would have detected particles with lifetime greater than 200 ns.

Heavy Particle Production Differential Cross Section

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE ($cm^2sr^{-1}GeV^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$<2.6 \times 10^{-36}$	90	0	[57] BALDIN	76	CNTR	−	Q= 1, m=2.1–9.4 GeV
$<2.2 \times 10^{-33}$	90	0	[58] ALBROW	75	SPEC	±	Q= ±1, m=4–15 GeV
$<1.1 \times 10^{-33}$	90	0	[58] ALBROW	75	SPEC	±	Q= ±2, m=6–27 GeV
$<8. \times 10^{-35}$	90	0	[59] JOVANOV...	75	CNTR	±	m=15–26 GeV
$<1.5 \times 10^{-34}$	90	0	[59] JOVANOV...	75	CNTR	±	Q= ±2, m=3–10 GeV
$<6. \times 10^{-35}$	90	0	[59] JOVANOV...	75	CNTR	±	Q= ±2, m=10–26 GeV
$<1. \times 10^{-31}$	90	0	[60] APPEL	74	CNTR	±	m=3.2–7.2 GeV
$<5.8 \times 10^{-34}$	90	0	[61] ALPER	73	SPEC	±	m=1.5–24 GeV
$<1.2 \times 10^{-35}$	90	0	[62] ANTIPOV	71B	CNTR	−	Q=−, m=2.2–2.8
$<2.4 \times 10^{-35}$	90	0	[63] ANTIPOV	71C	CNTR	−	Q=−, m=1.2–1.7, 2.1–4
$<2.4 \times 10^{-35}$	90	0	BINON	69	CNTR	−	Q=−, m=1–1.8 GeV
$<1.5 \times 10^{-36}$		0	[64] DORFAN	65	CNTR		Be target m=3–7 GeV
$<3.0 \times 10^{-36}$		0	[64] DORFAN	65	CNTR		Fe target m=3–7 GeV

[57] BALDIN 76 is a 70 GeV Serpukhov experiment. Value is per Al nucleus at $\theta = 0$. For other charges in range −0.5 to −3.0, CL = 90% limit is $(2.6 \times 10^{-36})/|(\text{charge})|$ for mass range (2.1–9.4 GeV) × $|(\text{charge})|$. Assumes stable particle interacting with matter as do antiprotons.

[58] ALBROW 75 is a CERN ISR experiment with E_{cm} = 53 GeV. θ = 40 mr. See figure 5 for mass ranges up to 35 GeV.

[59] JOVANOVICH 75 is a CERN ISR 26+26 and 15+15 GeV pp experiment. Figure 4 covers ranges Q = 1/3 to 2 and m = 3 to 26 GeV. Value is per GeV momentum.

[60] APPEL 74 is NAL 300 GeV pW experiment. Studies forward production of heavy (up to 24 GeV) charged particles with momenta 24–200 GeV (−charge) and 40–150 GeV (+charge). Above typical value is for 75 GeV and is per GeV momentum per nucleon.

[61] ALPER 73 is CERN ISR 26+26 GeV pp experiment. p >0.9 GeV, $0.2 < \beta < 0.65$.

[62] ANTIPOV 71B is from same 70 GeV p experiment as ANTIPOV 71C and BINON 69.

[63] ANTIPOV 71C limit inferred from flux ratio. 70 GeV p experiment.

[64] DORFAN 65 is a 30 GeV/c p experiment at BNL. Units are per GeV momentum per nucleus.

Long-Lived Heavy Particle Invariant Cross Section

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE ($cm^2/GeV^2/N$)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$< 5 \times 10^{-35}$–7×10^{-33}	90	0	[65] BERNSTEIN	88	CNTR		
$< 5 \times 10^{-37}$–7×10^{-35}	90	0	[65] BERNSTEIN	88	CNTR		
$<2.5 \times 10^{-36}$	90	0	[66] THRON	85	CNTR	−	Q= 1, m=4–12 GeV
$<1. \times 10^{-35}$	90	1	[66] THRON	85	CNTR	+	Q= 1, m=4–12 GeV
$<6. \times 10^{-33}$	90	0	[67] ARMITAGE	79	SPEC		m=1.87 GeV
$<1.5 \times 10^{-33}$	90	0	[67] ARMITAGE	79	SPEC		m=1.5–3.0 GeV
		0	[68] BOZZOLI	79	CNTR	±	Q = (2/3, 1, 4/3, 2)
$<1.1 \times 10^{-37}$	90	0	[69] CUTTS	78	CNTR		m=4–10 GeV
$<3.0 \times 10^{-37}$	90	0	[70] VIDAL	78	CNTR		m=4.5–6 GeV

[65] BERNSTEIN 88 limits apply at x = 0.2 and p_T = 0. Mass and lifetime dependence of limits are shown in the regions: m = 1.5–7.5 GeV and $\tau = 10^{-8}$–2×10^{-6} s. First number is for hadrons; second is for weakly interacting particles.

[66] THRON 85 is FNAL 400 GeV proton experiment. Mass determined from measured velocity and momentum. Limits are for $\tau > 3 \times 10^{-9}$ s.

[67] ARMITAGE 79 is CERN-ISR experiment at E_{cm} = 53 GeV. Value is for x = 0.1 and p_T = 0.15. Observed particles at m = 1.87 GeV are found all consistent with being antideuterons.

[68] BOZZOLI 79 is CERN-SPS 200 GeV pN experiment. Looks for particle with τ larger than 10^{-8} s. See their figure 11–18 for production cross-section upper limits vs mass.

[69] CUTTS 78 is pBe experiment at FNAL sensitive to particles of $\tau > 5 \times 10^{-8}$ s. Value is for $-0.3 < x < 0$ and p_T = 0.175.

[70] VIDAL 78 is FNAL 400 GeV proton experiment. Value is for x = 0 and p_T = 0. Puts lifetime limit of $< 5 \times 10^{-8}$ s on particle in this mass range.

Long-Lived Heavy Particle Production (σ(Heavy Particle) / $\sigma(\pi)$)

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$<10^{-8}$		[71] NAKAMURA	89	SPEC	±	Q= (−5/3,±2)
	0	[72] BUSSIERE	80	CNTR	±	Q= (2/3,1,4/3,2)

[71] NAKAMURA 89 is KEK experiment with 12 GeV protons on Pt target. The limit applies for mass $\lesssim$ 1.6 GeV and lifetime $\gtrsim 10^{-7}$ s.

[72] BUSSIERE 80 is CERN-SPS experiment with 200–240 GeV protons on Be and Al target. See their figures 6 and 7 for cross-section ratio vs mass.

Production and Capture of Long-Lived Massive Particles

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (10^{-36} cm^2)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<20 to 800	0	[73] ALEKSEEV	76	ELEC	τ=5 ms to 1 day
<200 to 2000	0	[73] ALEKSEEV	76B	ELEC	τ=100 ms to 1 day
<1.4 to 9	0	[74] FRANKEL	75	CNTR	τ=50 ms to 10 hours
<0.1 to 9	0	[75] FRANKEL	74	CNTR	τ=1 to 1000 hours

[73] ALEKSEEV 76 and ALEKSEEV 76B are 61–70 GeV p Serpukhov experiment. Cross section is per Pb nucleus.

[74] FRANKEL 75 is extension of FRANKEL 74.

[75] FRANKEL 74 looks for particles produced in thick Al targets by 300–400 GeV/c protons.

Long-Lived Particle Search at Hadron Collisions

Limits are for cross section times branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (pb/nucleon)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2	90	0	[76] BADIER	86	BDMP	$\tau = (0.05$–$1.) \times 10^{-8}$s

[76] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-X$, $\pi^+\pi^-\pi^{\pm}$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.

Long-Lived Heavy Particle Cross Section

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (pb/sr)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<34	95	[77] RAM	94	SPEC	$1015 < m_{X^{++}} < 1085$ MeV
<75	95	[77] RAM	94	SPEC	$920 < m_{X^{++}} < 1025$ MeV

[77] RAM 94 search for a long-lived doubly-charged fermion X^{++} with mass between m_N and $m_N + m_\pi$ and baryon number +1 in the reaction $pp \rightarrow X^{++}n$. No candidate is found. The limit is for the cross section at 15° scattering angle at 460 MeV incident energy and applies for $\tau(X^{++}) \gg 0.1\,\mu$s.

LIMITS ON CHARGED PARTICLES IN COSMIC RAYS

Heavy Particle Flux in Cosmic Rays

VALUE ($cm^{-2}sr^{-1}s^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$\sim 6 \times 10^{-9}$		2	[78] SAITO	90			$Q \simeq 14$, $m \simeq 370m_p$
$< 1.4 \times 10^{-12}$	90	0	[79] MINCER	85	CALO		$m \geq 1$ TeV
			[80] SAKUYAMA	83B	PLAS		$m \sim 1$ TeV
$< 1.7 \times 10^{-11}$	99	0	[81] BHAT	82	CC		
$< 1. \times 10^{-9}$	90	0	[82] MARINI	82	CNTR	±	$Q = 1$, $m \sim 4.5m_p$
$2. \times 10^{-9}$		3	[83] YOCK	81	SPRK	±	$Q = 1$, $m \sim 4.5m_p$
		3	[83] YOCK	81	SPRK		Fractionally charged
3.0×10^{-9}		3	[84] YOCK	80	SPRK		$m \sim 4.5\ m_p$
$(4 \pm 1) \times 10^{-11}$		3	GOODMAN	79	ELEC		$m \geq 5$ GeV
$< 1.3 \times 10^{-9}$	90		[85] BHAT	78	CNTR	±	$m > 1$ GeV
$< 1.0 \times 10^{-9}$		0	BRIATORE	76	ELEC		
$< 7. \times 10^{-10}$	90	0	YOCK	75	ELEC	±	$Q > 7e$ or $< -7e$
$> 6. \times 10^{-9}$		5	[86] YOCK	74	CNTR		$m > 6$ GeV
$< 3.0 \times 10^{-8}$		0	DARDO	72	CNTR		
$< 1.5 \times 10^{-9}$		0	TONWAR	72	CNTR		$m > 10$ GeV
$< 3.0 \times 10^{-10}$		0	BJORNBOE	68	CNTR		$m > 5$ GeV
$< 5.0 \times 10^{-11}$	90	0	JONES	67	ELEC		$m = 5–15$ GeV

[78] SAITO 90 candidates carry about 450 MeV/nucleon. Cannot be accounted for by conventional backgrounds. Consistent with strange quark matter hypothesis.

[79] MINCER 85 is high statistics study of calorimeter signals delayed by 20–200 ns. Calibration with AGS beam shows they can be accounted for by rare fluctuations in signals from low-energy hadrons in the shower. Claim that previous delayed signals including BJORNBOE 68, DARDO 72, BHAT 82, SAKUYAMA 83B below may be due to this fake effect.

[80] SAKUYAMA 83B analyzed 6000 extended air shower events. Increase of delayed particles and change of lateral distribution above 10^{17} eV may indicate production of very heavy parent at top of atmosphere.

[81] BHAT 82 observed 12 events with delay $> 2. \times 10^{-8}$ s and with more than 40 particles. 1 eV has good hadron shower. However all events are delayed in only one of two detectors in cloud chamber, and could not be due to strongly interacting massive particle.

[82] MARINI 82 applied PEP-counter for TOF. Above limit is for velocity = 0.54 of light. Limit is inconsistent with YOCK 80 YOCK 81 events if isotropic dependence on zenith angle is assumed.

[83] YOCK 81 saw another 3 events with $Q = \pm 1$ and m about $4.5m_p$ as well as 2 events with $m > 5.3m_p$, $Q = \pm 0.75 \pm 0.05$ and $m > 2.8m_p$, $Q = \pm 0.70 \pm 0.05$ and 1 event with $m = (9.3 \pm 3.)m_p$, $Q = \pm 0.89 \pm 0.06$ as possible heavy candidates.

[84] YOCK 80 events are with charge exactly or approximately equal to unity.

[85] BHAT 78 is at Kolar gold fields. Limit is for $\tau > 10^{-6}$ s.

[86] YOCK 74 events could be tritons.

Superheavy Particle (Quark Matter) Flux in Cosmic Rays

VALUE ($cm^{-2}sr^{-1}s^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.8 \times 10^{-12}$	90		[87] ASTONE	93	CNTR	$m \geq 1.5 \times 10^{-13}$gram
$<1.1 \times 10^{-14}$	90		[88] AHLEN	92	MCRO	$10^{-10} < m < 0.1$ gram
$<3.2 \times 10^{-11}$	90	0	[89] NAKAMURA	85	CNTR	$m > 1.5 \times 10^{-13}$gram
$<3.5 \times 10^{-11}$	90	0	[90] ULLMAN	81	CNTR	Planck-mass 10^{19}GeV
$<7. \times 10^{-11}$	90	0	[90] ULLMAN	81	CNTR	$m \leq 10^{16}$ GeV

[87] ASTONE 93 searched for quark matter ("nuclearites") in the velocity/c range = 10^{-3}–1. Their Table 1 gives a compilation of searches for nuclearites.

[88] AHLEN 92 searched for quark matter ("nuclearites"). The bound applies to velocity/c $< 2.5 \times 10^{-3}$. See their Fig. 3 for other velocity/c and heavier mass range.

[89] NAKAMURA 85 at KEK searched for quark-matter. These might be lumps of strange quark matter with roughly equal numbers of u, d, s quarks. These lumps or nuclearites were assumed to have velocity/c of 10^{-4}–10^{-3}.

[90] ULLMAN 81 is sensitive for heavy slow singly charge particle reaching earth with vertical velocity 100–350 km/s.

Highly Ionizing Particle Flux

VALUE ($m^{-2}yr^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.4	95	0	KINOSHITA	81B	PLAS	Z/β 30–100

REFERENCES FOR WIMPs and Other Particle Searches

ABE	97G	PR D55 R5263	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABREU	97D	PL B396 315	P. Abreu+	(DELPHI Collab.)
ACKERSTAFF	97B	PL B391 210	K. Ackerstaff+	(OPAL Collab.)
BARATE	97K	PL B405 379	R. Barate+	(ALEPH Collab.)
BERNABEI	97	ASP 7 73	R. Bernabei+	
SARSA	97	PR D56 1856	M.L. Sarsa+	(ZARA)
ALESSAND...	96	PL B384 316	Alessandrello, Brofferio, Camin+	(MILA, MILAI, SASSO)
BELLI	96	PL B387 222	+	(ROMA2, ROMAI, ROMA, ROMA3, BHEP)
Also	96B	PL B389 783 (erratum)	P. Belli+	
BELLI	96C	NC 19C 537	P. Belli+	(ROMA2, ROMAI, ROMA3, SASSO, BHEP)
BERNABEI	96	PL B389 757	+	(ROMA2, ROMAI, ROMA, ROMA3, BHEP+)
COLLAR	96	PRL 76 331		(SCUC)
SARSA	96	PL B386 458	+Morales, Morales, Garcia+	(ZARA)
Also	97	PR D56 1856	M.L. Sarsa+	(ZARA)
SMITH	96	PL B379 299	+Arnison+	(RAL, SHEF, LOIC, BIRK, NOTT)
SNOWDEN-...	96	PRL 76 332	Snowden-Ifft, Freeman, Price	(UCB)
AKERS	95R	ZPHY C67 203	+Alexander, Allison, Ametewee, Anderson+	(OPAL Collab.)
GALLAS	95	PR D52 6	+Abolins, Brock, Cobau+	(MSU, FNAL, MIT, FLOR)
GARCIA	95	PR D51 1458	+Morales, Morales, Sarsa+	(ZARA, SCUC, PNL)
QUENBY	95	PL B351 70	+Sumner+	(LOIC, RAL, SHEF, BIRK, NOTT, RHBL)
SNOWDEN-...	95	PRL 74 4133	Snowden-Ifft, Freeman, Price	(UCB)
Also	96	PRL 76 331	Collar	(SCUC)
Also	96	PRL 76 332	Snowden-Ifft, Freeman, Price	(UCB)
BECK	94	PL B336 141	+Bensch, Bockholt+	(MPIH, KIAE, SASSO)
RAM	94	PR D49 3120	+Abegg, Ashery, Frekers, Helmer+	(TELA, TRIU)
ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ASTONE	93	PR D47 4770	+Bassan, Bonifazi, Coccia+	(ROMA, ROMAI, CATA, FRAS)
BUSKULIC	93C	PL B303 198	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
YAMAGATA	93	PR D47 1231	+Takamori, Utsunomiya	(KONAN)
ABE	92J	PR D46 R1889	+Amidei, Anway-Weiss+	(CDF Collab.)
AHLEN	92	PRL 69 1860	+Ambrosio, Antolini, Auriemma, Baker+	(MACRO Collab.)
BACCI	92	PL B293 460	+Belli, Bernabei+	(Beijing-Roma-Saclay Collab.)
VERKERK	92	PRL 68 1116	+Grynberg, Pichard, Spiro, Zylberajch+	(ENSP, SACL, PAST)
AKESSON	91	ZPHY C52 219	+Almehed, Angelis, Atherton, Aubry+	(HELIOS Collab.)
REUSSER	91	PL B255 143	+Treichel, Boehm, Broggini+	(NEUC, CIT, PSI)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
ADACHI	90E	PL B249 336	+Anazawa, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
AKRAWY	90O	PL B252 290	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
HEMMICK	90	PR D41 2074	+Elmore+	(ROCH, MICH, OHIO, RAL, LANL, STON)
SAITO	90	PRL 65 2094	+Hatano, Fukada, Oda	(ICRR, KOBE)
NAKAMURA	89	PR D39 1261	+Kobayashi, Konaka, Imai, Masaike+	(KYOT, TMTC)
NORMAN	89	PR D39 2499	+Chadwick, Lesko, Larimer, Hoffman	(LBL)
BERNSTEIN	88	PR D37 3103	+Shea, Winstein, Cousins, Greenhalgh+	(STAN, WISC)
CALDWELL	88	PRL 61 510	+Eisberg, Grumm, Witherell+	(UCSB, UCB, LBL)
NORMAN	87	PRL 58 1403	+Gazes, Bennett	(LBL)
BADIER	86	ZPHY C31 21	+Bemporad, Boucrot, Callot+	(NA3 Collab.)
MINCER	85	PR D32 541	+Freudenreich, Goodman+	(UMD, GMAS, NSF)
NAKAMURA	85	PL 161B 417	+Horie, Takahashi, Tanimori	(KEK, INUS)
THRON	85	PR D31 451	+Cardello, Cooper, Teig+	(YALE, FNAL, IOWA)
SAKUYAMA	83B	LNC 37 17	+Nuzuki	(MEIS)
Also	83	LNC 36 389	Sakuyama, Watanabe	(MEIS)
Also	83D	NC 78A 147	Sakuyama, Watanabe	(MEIS)
Also	83C	NC 6C 371	Sakuyama, Watanabe	(MEIS)
BHAT	82	PR D25 2820	+Gupta, Murthy, Sreekantan+	(TATA)
KINOSHITA	82	PRL 48 77	+Price, Fryberger	(UCB, SLAC)
MARINI	82	PR D26 1777	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
SMITH	82B	NP B206 333	+Bennett, Homer, Lewin, Walford, Smith	(RAL)
KINOSHITA	81B	PR D24 1707	+Price	(UCB)
LOSECCO	81	PL 102B 209	+Sulak, Galik, Horstkotte+	(MICH, PENN, BNL)
ULLMAN	81	PRL 47 289		(LEHM, BNL)
YOCK	81	PR D23 1207		(AUCK)
BARTEL	80	ZPHY C6 295	+Canzler, Lords, Drumm+	(JADE Collab.)
BUSSIERE	80	NP B174 1	+Giacomelli, Lesquoy+	(BGNA, SACL, LAPP)
YOCK	80	PR D22 61		(AUCK)
ARMITAGE	79	NP B150 87	+Benz, Bobbink+	(CERN, DARE, FOM, MCHS, UTRE)
BOZZOLI	79	NP B159 363	+Bussiere, Giacomelli+	(BGNA, LAPP, SACL, CERN)
GOODMAN	79	PR D19 2572	+Ellsworth, Ito, Macfall, Siohan+	(UMD)
SMITH	79	NP B149 525	+Bennett	(RHEL)
BHAT	78	Pramana 10 115	+Murthy	(TATA)
CARROLL	78	PRL 41 777	+Chiang, Johnson, Kycia, Ki+	(BNL, PRIN)
CUTTS	78	PRL 41 363	+Dulude+	(BROW, FNAL, ILL, BARI, MIT, WARS)
VIDAL	78	PL 77B 344	+Herb, Lederman+	(COLU, FNAL, STON, UCB)
ALEKSEEV	76	SJNP 22 531 Translated from YAF 22 1021.	+Zaitsev, Kalinina, Kruglov+	(JINR)
ALEKSEEV	76B	SJNP 23 633 Translated from YAF 23 1190.	+Zaitsev, Kalinina, Kruglov+	(JINR)
BALDIN	76	SJNP 22 264 Translated from YAF 22 512.	+Vertogradov, Vishnevsky, Grishkevich+	(JINR)
BRIATORE	76	NC 31A 553	+Dardo, Piazzoli, Mannocchi+	(LCGT, FRAS, FREIB)
GUSTAFSON	76	PRL 37 474	+Ayre, Jones, Longo, Murthy	(MICH)
ALBROW	75	NP B97 189	+Barber+	(CERN, DARE, FOM, LANC, MCHS, UTRE)
FRANKEL	75	PR D12 2561	+Frati, Resvanis, Yang, Nezrick	(PENN, FNAL)
JOVANOV...	75	PL 56B 105	Jovanovich+	(MANI, AACH, CERN, GENO, HARV+)
YOCK	75	NP B86 216		(AUCK, SLAC)
APPEL	74	PRL 32 428	+Bourquin, Gaines, Lederman+	(COLU, FNAL)
FRANKEL	74	PR D9 1932	+Frati, Resvanis, Yang, Nezrick	(PENN, FNAL)
YOCK	74	NP B76 175		(AUCK)
ALPER	73	PL 46B 265	+	(CERN, LIVP, LUND, BOHR, RHEL, STOH, BERG+)
LEIPUNER	73	PRL 31 1226	+Larsen, Sessoms, Smith, Williams+	(BNL, YALE)
DARDO	72	NC 9A 319	+Navarra, Penengo, Sitte	(TORI)
TONWAR	72	JPA 5 569	+Naranan, Sreekantan	(TATA)
ANTIPOV	71B	NP B31 235	+Denisov, Donskov, Gorin, Kachanov+	(SERP)
ANTIPOV	71C	PL 34B 164	+Denisov, Donskov, Gorin, Kachanov+	(SERP)
BINON	69	PL 30B 510	+Duteil, Kachanov, Khromov, Kutyin+	(SERP)
BJORNBOE	68	NC B53 241	+Damgard, Hansen+	(BOHR, TATA, BERN, BERG)
JONES	67	PR 164 1584		(MICH, WISC, LBL, UCLA, MINN, COSU, COLO+)
DORFAN	65	PRL 14 999	+Eades, Lederman, Lee, Ting	(COLU)