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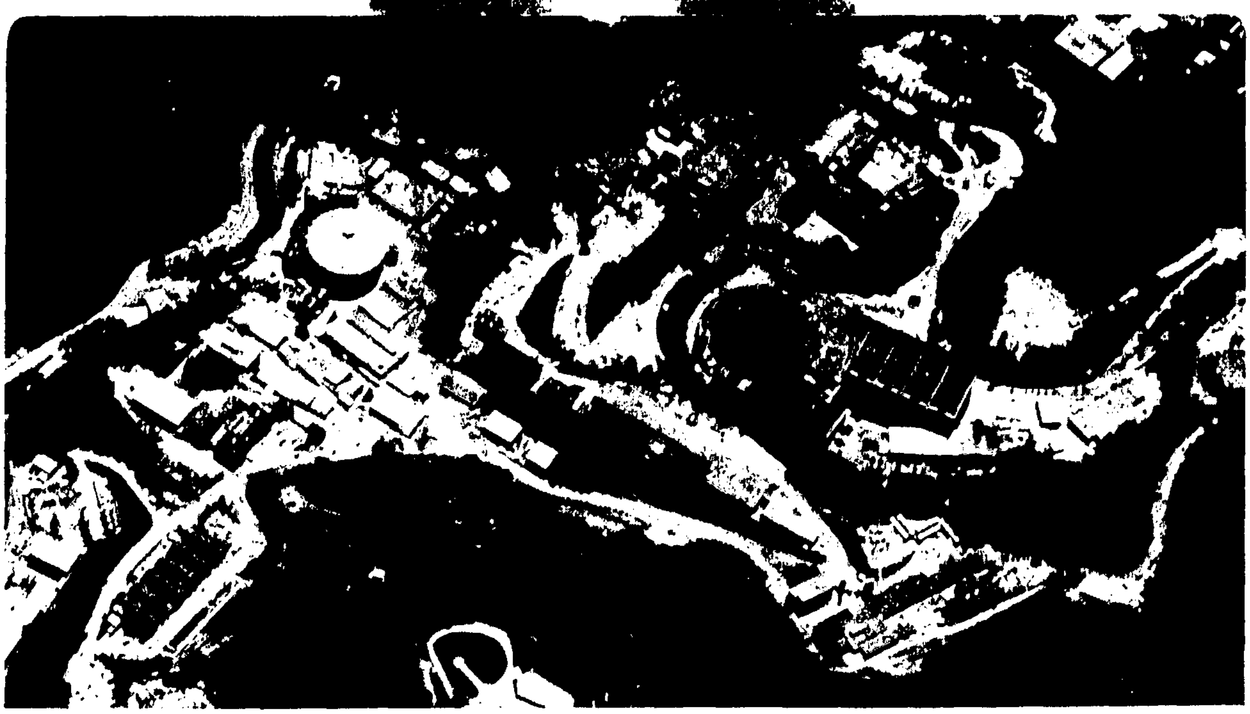

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Measurement of Energy Correlations in $e^+e^- \rightarrow$ Hadrons*

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ABSTRACT

Energy correlations have been measured with the MARK II detector at PEP at c.m. energy of 29 GeV and are compared to first order QCD predictions. Fragmentation processes are significant and limit the precision with which the first order strong coupling constant can be determined.

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We present a measurement of energy correlations of hadrons produced in high-energy e^+e^- annihilations. This measurement probes the general structure of hadronic events in a simple way and can be used to test QCD, the candidate theory of the strong interactions. It has several advantages over other techniques[1] of testing QCD: It does not require either the selection of specific event topologies, such as three-jet events, or the definition of a jet axis[2]. It uses a simple parameterization to account for the fragmentation process[3] rather than detailed Monte Carlo simulations. And, to first order, the backward-forward asymmetry in the correlation function is proportional to the strong coupling constant α_s. The first use of this general method of analysis was by the PLUTO group at PETRA[4].

The data reported here were taken at a center-of-mass energy of 29 GeV with the MARK II detector at the PEP storage ring of the Stanford Linear Accelerator Center and correspond to an integrated luminosity of 15000 events/nb. The essential features of the MARK II detector have been described previously[5].

Charged tracks are used in the analysis if they have a momentum greater than 100 MeV/c and appear to come from within 10 cm of the interaction point along the beam direction. Photons are used if they are measured to have an energy greater than 200 MeV in the lead-liquid argon calorimeters and are further than 10 cm from any charged track at the entrance of the calorimeters. Events are accepted if there are at least five charged tracks and at least one photon passing above criteria, if the total visible energy is larger than 15 GeV, and if the event vertex is within 7 cm of the interaction point in the beam direction and within a radial distance of 5 cm from the beam axis. The total visible energy is the sum of the energies of photons as measured in the liquid argon modules and of the energies of charged particles as measured in the drift chamber. Since we do not distinguish between particle masses, a pion mass has been assigned to all charged particles.

The fiducial volume for this measurement is taken to be $-0.7 < \cos\theta < 0.7$, where θ is the angle with respect to the incident beams, and the entire azimuthal acceptance with the exception of eight gaps of 6° width corresponding to the edges of the lead-liquid argon calorimeter modules. With the above selection criteria, 3000 events have tracks inside the fiducial volume.

The energy weighted cross section for observing the energy E in the solid angle $d\Omega$ and the energy E' in the solid angle $d\Omega'$ is defined by:

$$\frac{1}{\sigma_o}\frac{d\Sigma}{d\Omega d\Omega'} = \frac{1}{N d\Omega d\Omega'}\sum\sum\frac{EE'}{s} \quad . \qquad (1)$$

The first sum is over all pairs of particles in the solid angles $d\Omega$ and $d\Omega'$ while the second sum runs over all N events. The total hadronic cross section is denoted by σ_o , and the center-of-mass energy is $\sqrt{s}$. In this Letter we will study this cross section as a function of the angle χ between $d\Omega$ and $d\Omega'$. In order to obtain the cross section given in Eq. (1), corrections for the effects of resolution, detection inefficiency, initial state radiation and weak decays have been made by a Monte Carlo simulation. The sum of these corrections is small inside the fiducial volume and in the range of $20° < \chi < 160°$. They amount to 20% at $\chi = 20°$ and 5% at $\chi = 90°$.

The sum over all external angles keeping the opening angle χ fixed gives the following cross section:

$$\frac{1}{\sigma_o}\frac{d\Sigma}{d\cos\chi} = \frac{1}{N\Delta\cos\chi}\sum\sum\frac{EE'}{s} \quad . \qquad (2)$$

This corrected cross section summed over all pairs of particles inside the fiducial volume is shown in Fig. 1 as a function of $\cos\chi$ [6]. The peaks at $\cos\chi = +1$ and -1 show the tendency of the events to form into two back-to-back jets. Studying the deviations of the data from a two jet structure requires comparison with a detailed theoretical calculation. The cross section as defined in Eq. (1) has been calculated for partons in the framework of first order perturbative QCD[3,7]. The explicit form is:

$$\frac{1}{\sigma_o}\frac{d\Sigma}{d\Omega d\Omega'} = \frac{3}{16\pi}\left(A(\chi,\alpha_s)(2+\cos^2\theta+\cos^2\theta') + B(\chi,\alpha_s)(\cos\chi+\cos\theta\cos\theta')\right) \qquad (3)$$

The direction of a particle with respect to the beam is given by the polar angle θ. The functions A and B have been calculated in the framework of perturbative QCD to first order in α_s and they depend only on χ and α_s. They describe the energy correlation of a quark, antiquark and a gluon, according to the two external angular terms. In the partonic picture quark-antiquark events ($q\bar{q}$) contribute only at $\chi = 0°$ and $\chi = 180°$ to the energy correlation. The first order perturbative cross section has singularities at $\chi = 0°$ and $\chi = 180°$, where the gluon, quark, and antiquark become collinear. In the intermediate angular range ($20° < \chi < 160°$) there is a very pronounced asymmetry around $\chi = 90°$. Only those terms of the cross section proportional to α_s contribute to this asymmetry.

In order to compare the theory with an experiment, in which hadrons are observed instead of partons, a nonperturbative correction has to be added to account for the fragmentation of partons into hadrons[3]. The fragmentation of the $q\bar{q}$-process is in leading order symmetric around 90° and is accounted for by an additional term added to A. This term has been estimated to first order in $1/\sqrt{s}$ as:

$$A_{q\bar{q}f}(\chi) = \frac{A_f^0}{\sqrt{s}\,\sin^3\chi} \quad . \qquad (4)$$

A second fragmentation term for events with a gluon radiated off a quark or an antiquark ($q\bar{q}g$) has to be added to A. The dominant effect due to this fragmentation is to spread the correlation at 0° to larger values of the angle χ. This term is asymmetric with respect to 90° since for these three jet events there is no jet at 180°. Following the description of fragmentation of a quark according to Eq. (4) we tried the following ansatz to account for the fragmentation from $q\bar{q}g$ events[8]:

$$A_{q\bar{q}gf}(\chi) = \alpha_s \frac{A_f^1}{\sqrt{s}\,\sin^3\chi} \qquad \text{for } \chi < 90° \qquad (5a)$$

$$= \alpha_s \frac{A_f^1}{\sqrt{s}} (1+\cos\chi) \qquad \text{for } \chi > 90° \; ^9 \qquad (5b)$$

Equation (5) is only an estimate of the net contribution from $q\bar{q}g$-fragmentation, but it agrees well with a Monte Carlo simulation in the angular range 0° < χ < 80°. For angles > 80° the actual shape of the fragmentation term is less important since it is small there. As will be shown below, the addition of a fragmentation term like Eq. (5) is necessary in order to describe the data. Note that all terms which are asymmetric about χ = 90° come from three-parton processes and are thus proportional to α_s in this model.

The solid curve in Fig. 1 is the result of a fit of Eqs. (3-5), integrated over the MARK II solid angle. For the parameters we obtained $\alpha_s = 0.19 \pm 0.02$, $A^0{}_f = (0.7 \pm 0.2)$GeV and $A^1{}_f = (2.6 \pm 0.5)$GeV with a χ^2 of 25 for 22 degrees of freedom. The errors are statistical only. The fragmentation terms account for ≈40% of the observed correlation at χ = 90° (dashed curve in Fig. 1). The $q\bar{q}g$-fragmentation term is important in order to describe the observed energy correlation. A fit without this term ($A^1{}_f = 0$) increases χ^2 by a factor of two while the value of α_s changes to 0.14.

The measurement of the asymmetry $D(\chi) = 1/\sigma_0[d\Sigma/d\cos\chi(\pi-\chi) - d\Sigma/d\cos\chi(\chi)]$, which is given in Fig. 2, shows a change of nearly two orders of magnitude from χ =20° to χ = 90°. The full line is the sum of the pertubative and the $q\bar{q}g$-fragmentation component with parameters as determined from the full cross section. The fragmentation component contributes about 50% of the asymmetry.

The systematic error in α_s has been estimated to be 0.03. The major source of this error is the uncertainty in the form for the fragmentation terms, particularly Eq. (5). We have estimated the uncertainty by trying alternate forms of Eq. (5) that are roughly consistent with the shape predicted by the Monte Carlo simulations. The uncertainties from the fragmentation terms dominate the ones introduced by the Monte Carlo corrections.

There are two other sources of uncertainty which are not included in the error estimate because, in some sense, they are beyond the level of approximation we are considering. First, it is possible that the $q\bar{q}$ fragmentation has a second-order ,($\propto 1/s$), asymmetric component. Monte Carlo simulations indicate that such components exist and, if included, would reduce the value of α_s by about 10%. Second, no correction has been made for second-order perturbative terms in the cross section, because the calculation of them has not yet been done.

Our result is in good agreement with several determinations of α_s made at PETRA[10-13] from the observed number of 3-jet events, transverse momentum distributions and the thrust distributions. The PLUTO group has also determined α_s from a fit to the full energy correlation function of Eq. (3). The values of α_s from all these experiments are summarized in Table I. In this comparison one has to keep in mind that the systematic uncertainties come not only from different experimental methods but also from different treatment of the fragmentation. The energy correlation method treats the fragmentation with a global parametrization, whereas the other methods rely on Monte Carlo simulations.

In conclusion, the energy correlation cross section allows us to perform comparisons of QCD predictions with minimal use of a Monte Carlo model. Hadronisation effects even at this energy still contribute significantly to the opposite-side to same-side asymmetry. The perturbative QCD prediction with the additional fragmentation terms seem to agree rather well with the data. The strong coupling constant as defined in the first order QCD calculation of C.Basham et al., is in good agreement with results from other experiments.

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TABLE I

Values of α_s determined in various experiments around 30 GeV in the center-of-mass. The first error is statistical, while the second is systematic.

Experiment	α_s
MARK II	0.19 ± 0.02 ± 0.03
PLUTO[9]	0.20 ± 0.02
JADE[10]	0.18 ± 0.03 ± 0.03
MARK J[11]	0.19 ± 0.02 ± 0.04
TASSO[12]	0.17 ± 0.02 ± 0.03
PLUTO[13]	0.15 ± 0.03 ± 0.02

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6. Note that the cross section is for the fiducial volume and not extrapolated to the full solid angle.

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8. In the original work of C.Basham et al., the $q\bar{q}g$-fragmentation term has been neglected. Since the $q\bar{q}g$ term contributes mainly to one side of the energy correlation, it changes dramatically the opposite-side to same-side asymmetry (about a factor of ½ at 29 GeV).

9. In order to avoid a discotinuity at 90°, we have added a linear extrapolation to zero for χ > 90°.

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FIGURE CAPTIONS

1. $(1/\sigma_0)d\Sigma/d\cos\chi$ as a function of $\cos\chi$. The size of the dots corresponds to the statistical errors. The solid line is the QCD prediction of Ref. 5 including the nonperturbative contributions. The broken line is the nonperturbative part alone.

2. The asymmetry $D(\chi)$ as a function of $\cos\chi$. The solid line is the QCD prediction with α_s = 0.19 and $A^1{}_f$ = 2.6 GeV.

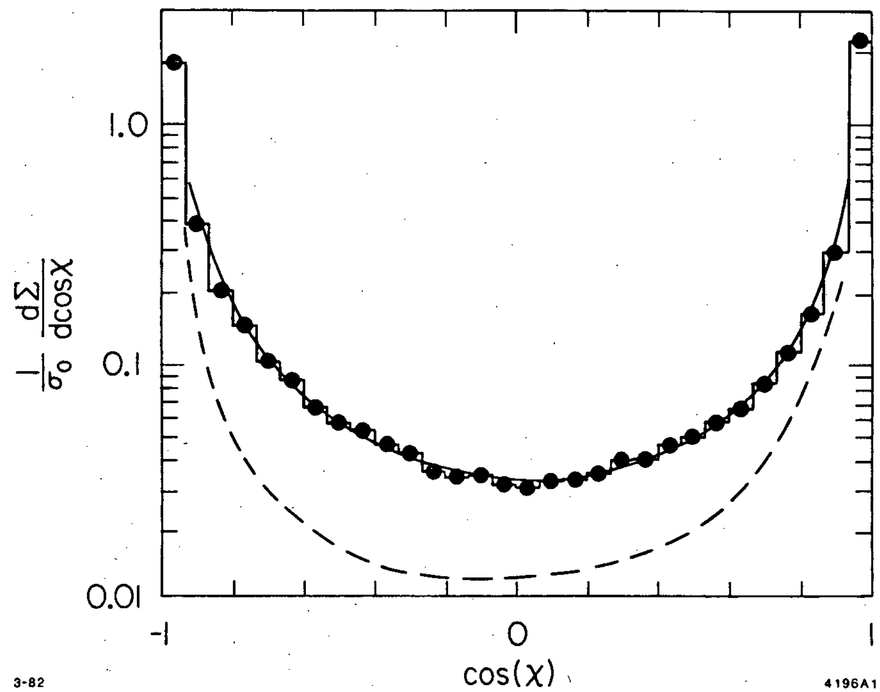

Fig. 1

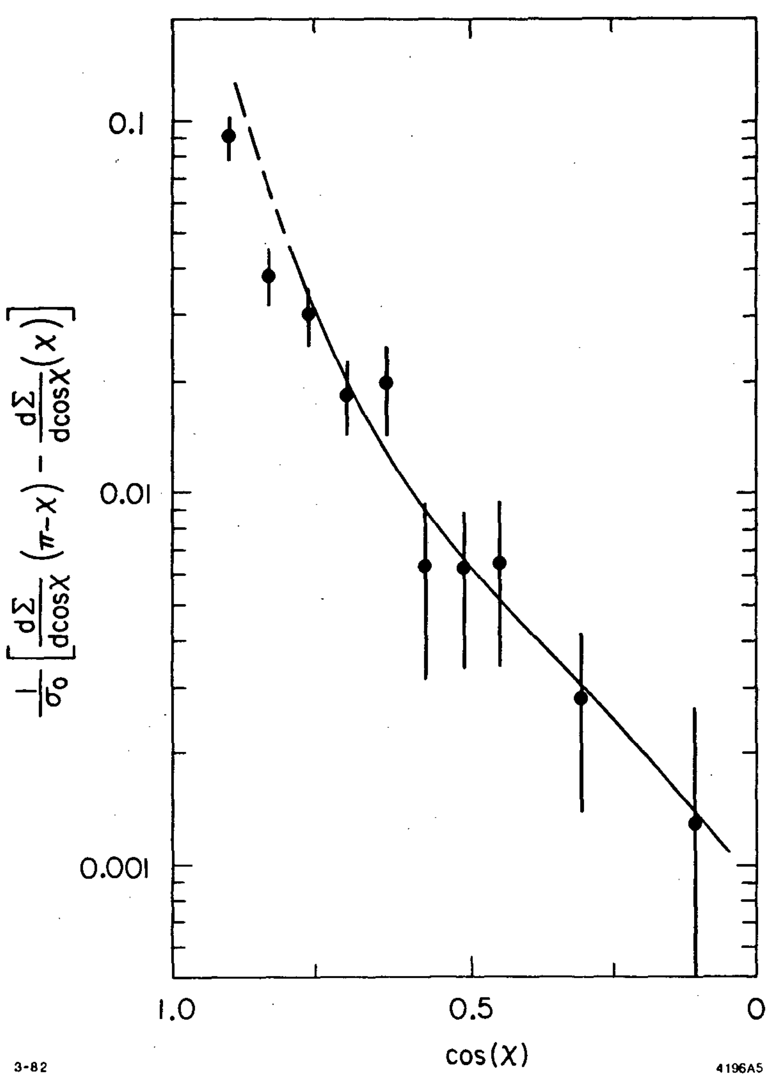
0.1
0.01
0.001
$\frac{1}{\sigma_0}\left[\frac{d\Sigma}{d\cos\chi}(\pi-\chi)-\frac{d\Sigma}{d\cos\chi}(\chi)\right]$
1.0
0.5
0
cos(χ)
3-82
4196A5

Fig. 2

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