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A contribution to the
Proceedings of the D.P.F. Summer Study
on the Design and Utilization of the SSC
June 23 - July 13, 1984
Snowmass, Colorado

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OVERVIEW OF PHYSICS ISSUES AT THE SSC

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Abstract.

This report presents an overview of physics issues at the SSC. It discusses the progress made at the DPF Summer Study on the Design and Utilization of the SSC and emphasizes the important problems which remain.

Introduction.

Since the first of these DPF Summer studies held in 1982,[1] much work has gone into thinking about the types of experiments which the SSC could perform and the answers that it could provide to the fundamental questions of nature. A number of workshops[2] have been held and detailed studies[3] made to clarify the physics issues relevant to the design and utilization of the SSC. Problems of machine design upon which the physics places critical demands are

(*a*) Do we prefer pp or $p\bar{p}$ interactions?

(*b*) What energy and/or luminosity will be sufficient to answer the physics questions that are the most pressing?

(*c*) What special requirements are placed on interaction regions? For example, small angle scattering experiments and total cross-section measurements will require a long interaction region.

(*d*) Does physics require polarization of the proton beams?

Some other issues, such as the bunch spacing and hence the number of interactions per crossing, are controlled more by questions of detector technology and experimental techniques rather than physics issues.

In addition, there are a number of areas where physics considerations are critical in the design and operation of detectors.

(*e*) How well can we pick out final states which have W's, Z's and heavy quarks? How efficient must we be in order to extract all of the physics?

(*f*) What is the minimum integrated luminosity needed to extract certain signals? Are any proposals too optimistic because they are making unrealistic demands upon detector technology?

I will divide my discussion of the physics issues into 'Standard Model', by which I mean the combination of QCD and the Weinberg-Salam model, and 'Non-Standard Physics', which includes supersymmetry, technicolor, new gauge bosons, compositeness and all the more or less speculative ideas in which theorists like to indulge. I will then discuss the work on identification of final states which contain W's, Z's or heavy quarks and comment upon the impact of this work on some proposed signals for new physics. Finally I will mention some of the areas in which more work is required. This report concentrates on the areas in which progress was made at the Workshop. It is not inteaded to be an exhaustive review of the status of SSC physics.

The Standard Model.

The main problems which were awaiting the standard model groups were

1. How well do we understand the QCD parton model? In particular, how reliable are its predictions which involve partons at small x?
2. Do we really understand the mechanisms which are responsible for the production of new strongly interacting particles?
3. How well do the algorithms used in Monte Carlo programs reflect what we understand about QCD?
4. Is it possible for the SSC to detect a Higgs boson in the mass range above that which is accessible at LEP, say 70 GeV/c^2?
5. Can the SSC make relevant measurements of the self couplings of the gauge bosons in the Weinberg-Salam Model?
6. Can experiments be performed which will cast new light on the problem of CP violation?

Strong Interactions.

The QCD parton model underlies almost all of the estimates of signals and backgrounds relevant to the SSC and other hadron colliders. Fundamental interactions which are probed in the search for new physics involve the collisions of quarks and gluons and, in some specialized cases, other particles, such as W's, which can appear as constituents of the proton. The rate for some new particle production is given by the following parton model formula,

$$\sigma(s) = \sum_{i,j} \int f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{i,j}(s x_1 x_2) dx_1 dx_2.$$

Here $\sqrt{\hat{s}} = \sqrt{s x_1 x_2}$ is the invariant mass of the parton-parton system and $\sqrt{s}$ is that of the proton-proton system. In this formula, $f_i(x, Q^2)$ is the probability of a parton of type i being inside the proton with fraction x of the proton's momentum. $\hat{\sigma}_{i,j}$ is the cross-section for the interaction of the two partons i and j. The scale Q appearing in the distribution functions is characteristic of the momentum transfers in the partonic process. In the case iof jet producton its value is somewhat ambiguous but is of order the jet transverse momentum. In the case of new particle production, the mass of the new particle is probably the appropriate value.

The distributions $(f_i(x, Q^2))$ are extracted from deep-inelastic scattering data at low Q^2 and then extrapolated to the higher Q^2 values appropriate to the SSC using the Altarelli-Parisi[4] equations of QCD. The kinematical range of the x_1 and x_2 integrals is $x_1 x_2 \geq \hat{s}_{min}/s$, where $\sqrt{\hat{s}_{min}}$ is the minimum, kinematically allowed, value of $\sqrt{\hat{s}}$. The distribution functions are rapidly falling functions of x, so that the dominant region of the integral comes from $x_1, x_2 \approx \sqrt{\hat{s}_{min}/s}$. At $\sqrt{s} = 40$ TeV, the production of a W boson is dominated by $x \approx .002$ and x as small as 4×10^{-6} is possible. These small values of x are not probed by current experiments which are confined to $x > 0.05$ and $Q^2 \leq 200$ GeV^2, so two problems arise.

Firstly, does the lack of data imply a very poor knowledge of the structure functions in this small x region? This issue was addressed by EHLQ,[3] by R.K. Ellis[5] at the LBL workshop, and by J. Morfin and J. Owens[6] in their summary of the work of the group looking at structure functions. The extraplolations of existing low Q^2 data into regions of small x are constrained somewhat by the various sum rules, but more importantly, as Q^2 is increased the behavior in this region is controlled by that for larger x at lower Q^2. Uncertainties at low x and Q^2 thus tend to be reduced as Q^2 rises.

Predictions of jet cross-sections at the $Sp\bar{p}S$ collider involve extrapolations of about one order of magnitude in Q^2 and seem to agree well with the data[7] (See figure 1 of ref. 6, which uses the distribution functions of Duke and Owens,[8] and figure 1 which is taken from EHLQ[3]). The predictions for single W and Z production also agree reasonably well with the data once the higher order QCD corrections (see below) are taken into account. Table 1 presents a comparison. The W and Z rates may not be a very good check on the distribution functions since the production is dominated by valence quarks, which are not so relevant at SSC energies.

Extraplolation does, of course, involve the value of the QCD scale parameter Λ which fixes the strong coupling constant. A clean determination of Λ requires the accurate measurement of a non-singlet structure function such as $xF_3(x, Q^2)$, otherwise only a coupled determination of Λ and the gluon distribution function is possible. Morfin and Owens[6] conclude that significantly better measurements of non-singlet structure functions are unlikely in the near future and that we cannot expect a signficant improvement in the value of Λ in the next few years. Hence, some uncertainty in the gluon distribution and in SSC predictions will remain.

Another problem is the heavy flavor content of the proton at high Q^2. EHLQ include bottom and top quarks in their distributions. Unfortunately, there is some ambiguity in the method for dealing with thresholds. The simplest method is to ignore heavy quarks (of mass m_Q) below threshold, i.e. when $Q^2 \leq 4m_Q^2$ and then to allow them to evolve in the same way as massless quarks once the threshold has been crossed. EHLQ have not done this, but rather have included some mass effects in the heavy quark evolution,[9] which tend to slow their rate of growth above threshold. The ambiguity cannot be resolved completely since the different prescriptions are all equivalent up to higher order QCD corrections which were neglected. In conclusion, it appears that the difficulties caused by current data are not severe and reliable predictions are possible provided that the second, more important question can be satisfactorily answered.

Does QCD perturbation theory in the form of the Altarelli-Parisi equations continue to apply at these small values of x? This vital question occupied one of the physics groups at Snowmass and the report by John Collins[10] should be consulted for details.

The QCD perturbation theory does indeed break down at small x, but the appropriate values of x are extremely small. An easy way to see that something must go wrong is to compute the cross section for, say, single W production as a function of s. In the region of small x, the structure function $f_i(x, Q^2)$ is proportional to x^{-a} with a of order 1.3.[3] The cross section for W production will then behave as $s^{(a-1)}\log s$. This behavior is unacceptable asymptotically and is an indication that the evolution of $f_i(x, Q^2)$ must ultimately change to cut off the growth at small x. This cut-off happens when the parton fraction, D, approaches 1,where D is defined by[11]

$$D(x, Q^2) = x f_i(x, Q^2) m_\pi^2 / Q^2.$$

There is a region in the (x, Q^2) plane where D is of order one or larger. In this region partons start to overlap, cease to act individually, collective effects become important and the simple parton model picture collapses. In his report, John Collins[10] has investigated this breakdown region. It is important not only that structure functions be used only when the fraction is small, but also that in the evolution of the Altarelli-Parisi equations from small Q^2 there are no sizeable contributions from regions of x and Q^2 where the equations are not valid. His conclusions are that the structure functions which are claimed to work for $x > 10^{-4}$ and $5\ \mathrm{GeV}^2 \leq Q^2 \leq 10^8\ \mathrm{GeV}^2$ are indeed valid over that range, so that the results obtained using them are reasonably reliable.

One final word of caution about distribution functions. Some of the radically different results for rates at the SSC which have appeared in the literature are due to misuse of distribution functions and do not represent some kind of extreme values showing the size of uncertainties. Care should be exercised when using a set of parameterizations of structure functions: these parameterizations usually have strictly limited ranges of applicability in x and Q^2 and can produce absurd results if used outside these ranges. Also, it is not legitimate to adjust the value of Λ in these parameterizations since they may not then agree with low energy data: Λ is usually strongly correlated with the gluon distribution, and these correlations are such as to tend to reduce differences at higher Q^2.

The reliability at small x has an interesting consequence. The fraction of events at the SSC which can be understood in terms of perturbative QCD will be much greater than at the $Sp\bar{p}S$ collider. The cross-section for events in which there are two jets of transverse momentum greater than 10 GeV each of rapidity $|y| \leq 2.5$ is shown as a function of $\sqrt{s}$ in figure 2. Estimates for the total cross section vary between 100 and 200 mb at SSC energies,[12] the value at $\sqrt{s} = 540$ GeV being about 60 mb.[13] Of course as s gets very large the probability of a double parton scatter (figure 3) will increase and the jet mutiplicity will start to rise.

Once we are certain that our predictions are free of small x disasters, the only uncertainty remaining concerns the accuracy of the evolved structure functions and the size of higher order QCD corrections to the parton-parton scattering cross-section $\hat{\sigma}_{i,j}$. These corrections are often ignored in making estimates, but they can be significant and give some indication about the size of the error on these estimates. For example, there are expected to be corrections of order 30 percent which increase the cross section for single W production.[14] The inclusion of these corrections at the $Sp\bar{p}S$ collider improves the agreement between the predictions and the data[7] (see Table 1). For most processes these corrections are not known; it would be valuable to have more calculations. In the case of jet production the corrections are known only for a small fraction of the 2 → 2 processes.[15] The knowledge of these corrections helps to resolve the ambiguities in the choice of the scale Q^2 which appears in the distribution functions.

A very important issue concerns the mechanism for the production of new strongly interacting particles. In the estimates most widely available, the pair production of such particles proceeds via the annihilation of a pair of gluons (or a quark and an anti-quark), one from each of the incoming beams (see figure 4). This production is centered around zero rapidity. There has been much discussion in the literature[16] of the so-called intrinsic mechanism for such production. This mechanism exploits the possibility of exciting the pairs of heavy strongly interacting particles which are present in the proton's wavefunction (see figure 5). If this latter mechanism is dominant then the production of new, strongly interacting particles will be diffractive so that they will emerge at small angles to the beam (large rapidity).

The existing data from the ISR on charm production[17] are indecisive, as are the data on charm production by muon beams.[18] The situation is reviewed by J. Richie[19] who concludes that the data are not good enough to either exclude or confirm the intrinsic mechanism. A measurement of the rate of hadronic top quark production at the $Sp\bar{p}S$ collider would help to clarify the experimental situation.

Since the intrinsic mechanism is non-perturbative a clean QCD prediction is not possible. The cross-section has the following approximate form

$$\sigma \approx f(M/\sqrt{s})/M^b.$$

Much energy was expended at the Workshop on attempting to understand the parameter b and hence the dependence of the intrinsic rate upon the heavy particle's mass (M). This will then allow an extrapolation from the existing upper bound on the intrinsic charm component at ISR energies to the intrinsic components of larger mass objects at the SSC. The fusion process has a mass dependence which corresponds to $b \approx 2$. Brodsky et al.[20] have concluded that the mass dependence of the intrinsic mechanism is $b \approx 4$. Since the charm production rate at the ISR from the intrinsic mechanism cannot be much greater than that from the fusion mechanism, this result would imply that the intrinsic mechanism will not be important for the production at the SSC of particles heavier than about 30 GeV.

Given our current understanding of QCD, it is fair to conclude that the predictions for rates at the SSC which involve the production of particles of mass (or transverse momentum) greater than 50 GeV or so are accurate to better than a factor of two unless some new physics intervenes. The production of lighter states such as $b\bar{b}$ pairs is less reliably known. Predictions of these rates require distribution functions at small x *and* Q^2 which are less reliable. In addition, the intrinsic mechanism could be important.

Having understood the behavior of QCD it is important that its characteristics be correctly incorporated into the various Monte-Carlo event generators which are used for discussing signals and backgrounds. Two such generators were available at the Workshop, FIELDAJET,[21] written by R. Field, and ISAJET[22] written by F. Paige and S. Protopopescu. The latter is faster and has many new physics processes such as the production and decay of pairs of supersymmetric particles already built in. These programs differ in the way that they deal with parton cascades.

Consider the production of a jet-jet final state with large transverse momenta. Two incoming partons undergo a large p_T scatter to produce two outgoing partons which then hadronize, producing the final state jets. The scattering partons have invariant mass $Q \approx p_T$. A parton shower involving the emission of quarks and gluons takes place from the incoming and outgoing lines (see figure 6). This shower must stop at some scale μ where perturbative QCD ceases to be relevant. Clearly $\mu > 1$ GeV, but its exact value is a parameter which can be freely adjusted. The dominant part of the shower arises from the regions of phase space where the shower fragments are either soft or are moving parallel to the parent. The initial state shower is therfore dominantly along the beam direction. The fragmentation of these partons then produces final state hadrons.

ISAJET does not allow such a shower to form from the incoming partons; emission from outgoing partons which leads to jet broadening is included. This prescription is not gauge invariant. It leads to jet events in which the particles in the event which do not belong to the jets are distributed in the same way as those in events which do not contain jets (minimum bias events). FIELDAJET has this initial gluon emission and consequently produces more non-jet particles than are present in minimum bias events. This difference is shown in figure 7 which is taken from the group report of K. Ellis and J. Rohlf[23] (see also J. Huston[24]). This figure shows that the data from the UA1 experiment[25] which seem to favor FIELDAJET.[24] However, FIELDAJET produces more three and four jet events than are seen in the data. Huston concludes that the truth seems to be somewhere between the clean structures produced by ISAJET and the messy ones produced by FIELDAJET.

A generator due to Odorico,[26] which was not available at the Workshop, also has the initial state radiation and seems to agree rather well with the data from the $Sp\bar{p}S$ collider.[30]

The development of these QCD showers is predicted by QCD perturbation theory. The simplest algorithm is the leading pole approximation. This algorithm is used by ISAJET, FIELDJET and by Odorico. In this approximation a parton of invariant mass M is allowed to split into two partons of smaller mass with a well defined probability; it is the Altarelli-Parisi splitting function. This approximation is correct in the limit that the final state momenta are colinear with the momentum of the decaying parton. This region gives rise to the dominant part of the QCD evolution and is the origin of the scaling violations expected in jet fragmentation, so this approximation gives a reasonable representation of QCD. The shower generated by this algorithm is incoherent; a more exact algorithm must include some coherence effects. The simplest of these effects is associated with the emission of soft gluons. The emission of such a soft, and hence long wavelength gluon is controlled not by just its 'parent', but also by any other gluons which are within the soft gluon's wavelength. Surprisingly, this simplest effect can be incorporated into the classical branching process by modifying the branching probability.[27] The effect of these coherence contributions is to reduce the emission probability for a soft gluon and hence to produce a cleaner final state.

These Monte-Carlo generators are capable of producing multi-jet final states. The algorithm used is the leading pole approximation. For example, a three jet final state is generated from a state with two partons one of which has a large invariant mass and decays into two partons with smaller invariant masses and a non-zero opening angle. As we have seen, this approximation will yield correct results only in regions of phase space where the jets are almost colinear and invariant mass of a pair of jets is rather small. Exact QCD calculations[28] are available for the production of three jets so the approximation can be tested. This was done by R. K. Ellis and J. Owens[29] (see figure 2 of ref. 29) who concluded that the approximation is good to no better than a factor of two or so. This important result makes it imperative that multi-jet final states be correctly incorporated into the Monte-Carlo generators. For the four or more jet final states, the relevant QCD calculations are not yet available.

This deficiency in Monte-Carlo generators should be remedied as soon as possible since some of the background calculations could be affected. For example, the final state $W +$jets is a background to $W + W$, if one of the W's decays hadronically. In this case, the state $W +$ two jets is important and should be generated correctly.

Having produced a final state consisting of partons, the next step for any Monte-Carlo generator is to hadronize this partonic system. The standard hadronization proceedures are discussed and contrasted by M. Derrick and T. Gottschalk.[30] The simplest method is to allow each parton to fragment to hadrons independently[31] of the other partons in the event. This approach is taken by both ISAJET and FIELDAJET. Several other approaches are possible. In the cluster model,[32] final states of color neutral partons with some low invariant mass are allowed to decay to hadrons. In the simplest version only two body decays are allowed and the branching ratios are fixed from phase space alone. In the string picture[33] color neutral strings are fragmented. This is easy to implement in e^+e^- annihilation, where, for example, the two jet final state consists of a $q\bar{q}$ pair connected by a color string. This string then breaks, generating an additional $q\bar{q}$ pair at the break. In a hadronic collision, the presence of colored particles in the initial state makes it rather difficult to keep track of the color flow.[30] The string fragmentation picture is therefore not easy to implement in Monte-Carlos for hadron colliders.

Most fragmentation studies have been carried out in e^+e^- annihilation and the independent fragmentation picture is disfavored.[30] We are therefore in the unfortunate situation that all the hadron collider Monte-Carlos are using a fragmentation picture which disagrees with the best available data. The fragmentation of heavy and light quarks is known to be quite different at energies not far above the heavy quark mass. In particular, the distribution in $z(= E_{\text{hadron}}/E_{\text{jet}})$ has more support at high z for a heavy quark jet than a light quark jet. This has been suggested as a method by which top quark jets could be distinguished from other jets at the SSC (see below).

Heavy quark pairs can be generated inside light quark jets via the QCD process gluon $\rightarrow Q\overline{Q}$, which can occur in the shower development. This rate is predicted by QCD perturbation theory and is quite small, [22] of order 0.05 $t\bar{t}$ pairs in a 500 GeV gluon jet. However, the measurement of of D^* production by the $UA1$ group[34] indicates that it is at a rate which is much larger than that which would be suggested by this perturbative picture. These data imply that a substantial non-perturbative component is needed. The impact of this result on top quark rates at the SSC is not clear. The detailed study of jet fragmentation in hadron colliders is in its infancy. As more data become available the ambiguities in the fragmentation prescriptions will be reduced, hopefully yielding a more reliable picture of the detailed properties of jets to be expected at the SSC.

One area of strong interaction physics which cannot be understood at present from QCD is that of low transverse momentum phenomena.[35] The total cross-section in proton-proton scattering, as well as the multiplicity and the distribution of the particles produced at low transverse momentum are characterized by small momentum transfer where the QCD coupling constant is large and no reliable calculational techniques are available. Our lack of understanding of these (old) phenomena does not imply that they are not interesting. While it is true that the fundamental discoveries of the SSC are unlikely to involve low transverse momenta, particularly if the conclusions on intrinsic production of new particles are correct, careful measurements have the potential to improve our understanding of QCD.

Issues relating to the total cross-section are discussed by Marty Block.[36] The total cross-section predictions for the SSC range from 100 to 200 mb. The lower value was assumed in the reference design. It is a critical quantity since it controls the number of interactions per beam crossing.

In order to measure the total cross-section at the SSC it is necessary to measure elastic proton-proton scattering at a sufficiently small angle so that the contribution from Coulomb scattering is the same order as that from strong interaction scattering. This implies a scattering angle as small as 0.5 μrad, and a measurement at about 4 km from the interaction point. Jay

Orear[37] discusses in detail how such measurements could be made.

The distribution of beam fragments in the ISAJET Monte-Carlo is adjusted to fit the data from existing experiments and is not inspired by theoretical ideas based on QCD about how the distribution may behave as a function of energy. Its predictions at the SSC for such distributions may be unreliable. There was considerable discussion of such distributions and in particular of the approach to KNO scaling.[38] The quantity $N_{\text{average}}p(N)$, where $p(N)$ is the probability of multiplicity N occurring, is a function only of N/N_{average} and is independent of $\sqrt{s}$ in the KNO limit. The data show approximate scaling.[39] The deviations from this simple form could be a clue to the dynamics of low p_T physics, just as the deviations from Bjorken scaling yield information about perturbative QCD effects. In particular, KNO scaling violations inspired by QCD[40] predict an approach to scaling which is different from that of other models.[38,41] The existing data seem to favor the QCD inspired form.[40]

Electroweak Interactions.

In the area of electroweak interactions,[42] most attention was focused on the detection of the minimal Weinberg-Salam model Higgs boson. This is one of the most difficult states for the SSC to find. It has a rather small production cross-section, and, if light, a very poor signature.

If it is light enough, the Higgs boson can be observed at the next generation of e^+e^- machines, LEP or SLC, via the reactions $e^+e^- \rightarrow Z \rightarrow H\mu^+\mu^-$ [43] or $e^+e^- \rightarrow ZH$.[44] The production at the SSC is dominated by that from gluon-gluon fusion,[45] if the mass is less than approximately 350 GeV, or by WW fusion[46] otherwise (see figure 8). In the latter case, an approximation has been used to estimate the rate. This approximation, which assumes that the gauge bosons are colinear with the incoming quarks has been compared with the exact result in a paper contributed by S. Dawson.[47]. It is accurate to better than twenty per cent over the relevant range of Higgs masses. The Higgs production cross-section is a rather weak function of its mass. In the range 100 – 1000 GeV it falls from 1 nb to 1 pb.

If the Higgs mass is greater than twice the W or Z mass then it will decay dominantly into W or Z pairs. The background in these channels from W or Z pair production via $q\bar{q}$ annihilation has been shown not to be a problem.[3,48] Even if the Z pair mode is detectable only via the leptonic decays of the Z's it should still be possible to detect a Higgs boson if experiments are possible with an integrated luminosity of 10^{40}cm^{-2}. The observability of W and Z final states in their hadronic decay modes will greatly ease the detection of such a Higgs boson. This observability will be discussed below.

There is a region of Higgs masses above that which is observable at the e^+e^- machines, but below twice the W mass where the Higgs will decay dominantly into a $t\bar{t}$ quark pair. I will assume a t quark mass of order 45 GeV in what follows. There is a large background from the production of $t\bar{t}$ pairs via gluon fusion. This background totally overwhelms the signal, making the observation exceedingly difficult.[3] The best chance for detection seems to be by observing the final state HW, where the W is tagged from its leptonic decay. The background now comes from final states of $W + t\bar{t}$. Gunion et al.[49] have demonstrated that, given a resolution of order 0.1 on $\Delta M_{t\bar{t}}^2/M_{t\bar{t}}^2$, the signal exceeds the background. Unfortunately, the cross-section is rather small. If both the W and H are produced centrally, having $|y| \leq 2$, and the W has $p_T > 40$ GeV (both of these cuts enhance the signal to background ratio), then it is of order 120 fb, for Higgs masses around 130 GeV if the W is required to decay either to $e\nu$ or to $\mu\nu$.

There is a large background from the process with a final state of $Wt\bar{b}$, which will be serious if good t/b rejection is not available. With the same cuts and resolution on ΔM^2, this rate is approximately 50 times the signal.[49] Good b quark rejection is therefore vital if this process is to be exploited; I will return to this issue when I discuss t quark identification below.

The issue of precision measurements of the self-couplings of gauge bosons also received some attention. A measurement of the $WW\gamma$ coupling is possible once W pair production is observed in e^+e^- annihilation. It seems reasonable that any measurements at the SSC will not be important unless they can have a precision of ten per cent or less. S. Matsuda and J. Owens[50] considered the possibilities for measuring the W magnetic moment. They concluded that the large background from W+jet in which the jet fragments in such a way as to fake a single photon, is so severe that a measurement with more accuracy than a factor of two is probably not possible.

If the Higgs mass becomes very large then its couplings to itself and to longitudinally polarized W's and Z's become very large. The width of the Higgs calculated perturbatively,

$$\Gamma_H \approx 58 \left(\frac{M_H}{500\text{GeV}}\right)^3 \text{GeV},$$

becomes very large and it is difficult to speak of a resonance. In this case one is dealing with a strongly coupled system consisting of W's and Z's. The problems of predicting its behavior are similar to those of calculating hadron masses in QCD.

Several methods have been tried in order to make estimates of the consequences of such strong coupling. One method predicts the existence of a scalar bound state of mass below 1 TeV.[51] Such a bound state will behave in a similar way to the elementary Higgs. This prediction is based on a power series expansion in $1/N$ where the gauge group of the interactions is $SU(N)$. $N = 2$ for the case of interest, so there must be some doubt concerning the validity of the method.

There are several qualitative features which should occur.[52,53,54] Structure should appear in multi-W final states when the the invariant mass of the multi-W system is of order 1 TeV. Examples of this structure include

(*a*) A larger ratio of 3W and 4W final states to 2W final states than is predicted on the basis of quark anti-quark annihilation.

(*b*) A ratio of Z pair to W pair cross sections which is larger than that expected from quark anti-quark annihilation. Furthermore this ratio should be larger at large pair masses.

(*c*) Variation of the W and Z pair cross-sections with the invariant mass of the pair which is different from that expected from production via quark anti-quark annihilation.

In the case of two and three gauge boson final states some estimates of the rates are possible by considering the production and decay of a 1 TeV Higgs boson produced either alone, which will generate a two gauge boson final state, or in association with a W or a Z, which will produce a three gauge boson final state. The ratio of cross sections with three and two gauge bosons obtained in this manner is similar to that obtained by using 'soft W theorems'[53] which are analagous to the soft pion theorems of QCD. Estimates[53,54] for the three boson final state yield about 200 fb in the interesting invariant mass region. The rates for final states with four gauge bosons will be less. Even if the W sector is not strongly interacting, there will be final states of three and four gauge bosons produced from $q\bar{q}$ annihilation. The rate will fall rapidly as the invariant mass of the multi-W system rises. This background is not known, however, as I shall discuss below, it may not be relevant since the observability of these small rates is in doubt.

In variants of the minimal Weinberg-Salam model the Higgs sector is usually easier to detect.[55] The simplest variant is a model with two Higgs doublets, in which there are four physical scalar particles, three neutral and one charged. The neutral ones behave in much the same way as the minimal Higgs except that the couplings of some of them to quarks and leptons can be enhanced. This enhancement will increase their production rates at the SSC. The charged Higgs may be produced in pairs via the Drell-Yan mechanism or singly via $q\bar{q}$ annihilation. In either case the rates are likely to be small.[56] In models with Higgs particles in representations other than doublets, the charged Higgs may have a coupling to WZ. In this case, a heavy H^+ will decay to WZ producing a better signature. It can be produced singly via WZ fusion (see figure 8(b)) at a rate comparable to that of the minimal Higgs.

The total cross-section for the production of $b\bar{b}$ quark pairs is expected to be very large. The estimate for primary production via gluon-gluon fusion is of order 200 μb.[22] This estimate is rather uncertain since it involves parton distributions at $x \approx 10^{-4}$ *and* low Q^2 where the EHLQ distributions may be rather unreliable. In addition there can be production of $b\bar{b}$ pairs in the fragmentation of quark and gluon jets, and possibly by the intrinsic mechanism.

These large rates have led to much speculation[58] concerning the possibilities for studying rare decays. Like the strange mesons, but unlike the charm and top mesons, the allowed decays of the B mesons are suppressed by small values of the Kobayashi-Maskawa[57] mixing angles which results in a large value for the B lifetime. This long lifetime has encouraged further optimistic comments since it raises the possibility of tagging the B's with a vertex detector.

The only system in which CP violation has been studied is that involving the neutral kaons. The system involving neutral B mesons, either $b\bar{d}$ or $b\bar{s}$

will behave in a manner similar to that of the kaons. One could hope to see $B - \overline{B}$ mixing and CP violation. The obvious signal for this mixing is obtained by looking for a final state with a semi-leptonic decay from each of the b's. If we denote by N^{++} the number of final states with two semi-leptonic decays where leptons are positively charged, then the mixing is signalled by a non zero value for the ratio

$$A = \frac{N^{++} + N^{--}}{N^{++} + N^{--} + N^{-+} + N^{+-}}$$

and the CP violation by

$$B = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

having a non-zero value.

In the standard model A is expected to be of order 0.05 for the $b\overline{d}$ system and of order 0.2 for the $b\overline{s}$ system[59]. These rates are probably large enough to measure, and are likely to be measured at LEP where the cross-section for $b\overline{b}$ production is expected to be as large as 30 nb if the $b\overline{b}$ pair is produced from the Z^0. B is expected to be much smaller, of order 10^{-3}. This quantity is also rather difficult to measure accurately, the initial state (pp) is, after all, not charge symmetric and there are many other sources of leptons.

For these reasons Cronin et al.[59,60] decided to concentrate on a specfic decay mode of one of the B's. The final state ψK_S is a state into which both B and $\overline{B}$ mesons can decay. CP violation can be observed by triggering on this decay mode and then looking at semi-leptonic decays of the other b. If we define NP^+ to be the number of final states with ψK_S and a semi-leptonic decay yielding a positively charged lepton, the CP violation parameter C is expected to be of order .05 where

$$C = \frac{NP^+ - NP^-}{NP^+ + NP^-}$$

One of the most serious unknowns in a rate estimate is the branching ratio for $B \to \psi K_S$. A limit from CLEO[61] of 0.01 for the branching ratio $B \to \psi + \text{anything}$ exists. Cronin et al. assumed a value of 0.001 for the exclusive mode. They also require that the B's be produced more than 30° from the beam with a transverse momentum of more than 10 GeV/c in order to ensure a reasonable flight path for vertex detection. After efficiency factors they conclude that there will be of order 1300 detected ψK_S + lepton events for an integrated luminosity of 10^{39}cm^{-2}.

In view of the comments made at this Workshop concerning the possibilities of vertex detectors surviving at high luminosity,[62] this last assumption may be optimistic. It will therefore be very difficult to observe CP violation in the B system if it occurs at the rate indicated by the standard model. Of course, the standard model could be wrong; an effect at the twenty per cent level in this exclusive mode is observable.

Non Standard Models

The main questions here were

1. What are the distinctive signatures for new physics?
2. Can these signatures be extracted from the backgrounds?
3. What are the definitive experiments which can be made to test the new models?

Previous discussions of the SSC experiments to search for deviations from the standard model have concentrated on the simplest signatures without a detailed discussion of the backgrounds using Monte-Carlo generators. At the workshop considerable work was done on the details of the signals, and attempts were made to determine whether this previous work had been too optimistic. The general conclusion was that it had not, and nothing was unearthed at the workshop which would indicate that any very serious problem had been overlooked.

Extensions to the standard model fall into four basic categories. Two of these, supersymmetry[63] and technicolor,[64] attempt to solve the theoretical problems associated with the Higgs sector of the Weinberg Salam model. We do not understand where the scale of weak interactions ($\simeq$ 250 GeV) comes from, and in particular, cannot explain why it is so much less than the only other fundamental scale in physics of which we are aware, namely the scale appearing in Newton's constant ($M_P \approx 10^{19}$GeV). There may be one other scale, that of grand unification but we have at present no definite experimental evidence for it. (Values around 10^{14}GeV or greater are favoured by most theorists, but a much lower scale is possible.)

This large discrepancy in scales (the hierarchy problem) is made all the more acute by the behavior of scalar masses in perturbation theory. Unlike fermion masses, they receive radiative corrections which are quadratically divergent. A very delicate fine tuning is required at each order of perturbation theory to maintain the hierarchy. There is also some suggestion that (non-supersymmetric) theories which have elementary scalars may be fundmentally flawed.[65] The two approaches used to attack this Higgs problem have radically different philosophies. One elliminates elementary scalars completely and replaces them with bound states of fermion-anti-fermion pairs (technicolor theories). The other introduces more elementary scalars (the partners of quarks and leptons) as it makes the theory supersymmetric.

The other non-standard models have somewhat different motivation. Theories with more gauge bosons which mediate new weak interactions[66] are motivated by the explicit breaking of parity in the Weinberg-Salam model. These theories have more W's which couple to right handed quarks and leptons. At energy scales much greater than the mass of these new W's, the theory will conserve parity if the couplings of these new W's are equal to those of the Weinberg Salam model W's. Parity breaking thus becomes a low energy phenomenon.

Some theorists have also become concerned about the proliferation in the numbers of quarks and leptons. In the same way that the proliferation of hadrons led to the introduction of quarks, so it has been suggested that quarks and leptons are composed of more fundamental objects ('preons').[67] There are limits on the scale of binding of these preons from existing experiments; it must be of order 1 TeV or so.[68] The exact value depends to some extent on the nature of the new residual couplings between quarks and leptons which are remnants of this new binding interaction. If these couplings violate baryon number, or can produce flavour changing neutral current reactions of the type $K_0 \rightarrow \mu e$, the limits on the scale of the new interactions are much greater. They are so large that composite effects will be almost impossible to detect at the SSC.[69]

The first two non-standard options make definite predictions concerning the energy scale of their new physics. Since they are attempting to solve the Higgs problem, they predict new physics at the scale of weak interactions, say 1 TeV. The general properties of these theories can be definitively tested at the SSC and their basic ideas ruled out if nothing is found. The last two options do not have this feature. In these cases there is no particular reason for their new physics to be apparent on the energy scale of the SSC. Some theorists who believe in composite models would favor a binding scale of order M_p.[70]

It is possible for either or both of the last two options to occur along with either of the first two. Strictly speaking, is is also possible for the first two to coexist with each other, but most theorists regard this as extremely unlikely.

I will briefly discuss each of these options in turn, highlighting the progress made in each area at the workshop. It is interesting to note that the requirements placed on detectors by searches for technicolor and by supersymmetry are almost orthogonal. The former requires discrimination between different types of jets and good W identification whereas the latter needs very good energy measurements and the ability to tag events with missing transverse momentum.

Technicolor theories have received a great deal of attention and the particle spectrum predicted by a prototypical model[71] discussed in detail.[3] In these theories the elementary Higgs is replaced by a pseudo-scalar bound state of some new techniquarks,[72] analagous to the pion in QCD, and generically called technipions. The technicolor force responsible for the binding of the techniquarks can be assumed to be due to a non-Abelian gauge theory, say $SU(N_{tc})$, in which case many general conclusions can be drawn by analogy with QCD. There have to be at least three technipions in order to give mass to the three gauge bosons W^+, W^- and Z. Realistic models have more than the minimum number.

All technicolor theories will predict the existence of a spin one boson, the techni-rho (analagous to the rho meson in QCD). The mass of this techni-rho can be inferred if we assume that the dynamics responsible for the binding of the techniquarks is similar to QCD with a larger Λ parameter. Since the scalars are resposible for generating the W mass, this parameter will be of order 250 GeV (the vacuum expectation value of the Higgs field in the minimal Weinberg-Salam model). The mass of the techni-rho will depend on the number of technicolors (N_{tc}).

$$M_{tc-\rho} = 2\sqrt{3/N_{tc}} \text{ TeV}$$

This techni-rho will show up as a resonance in the two gauge boson channel at the SSC, just as the rho appears as a resonance in $\pi\pi$ scattering. The production rate is shown as a function of N_{tc} in figure 9. The event rate is not large. The feasabilty of this experiment to search for an excess of events in final states with two gauge bosons depends critically upon the efficiency with which the bosons can be detected and will be discussed below.

As well as the techni-rho, the model will also contain bound states of N_{tc} techniquarks. There will therefore be techni-baryons with masses of order $0.5\sqrt{N_{tc}}$ TeV, the analogues of the proton in QCD. We have the general feature that as the techni-baryon mass increases, the techni-rho mass decreases.

In more realistic technicolor models many more states are predicted. The prototypical model is the Farhi-Susskind[71] model. In this model there are many pseudoscalar techni-mesons with masses less than 1 TeV. The masses and couplings of these states are model dependent but the features that they represent are sufficiently general to merit detailed studies of the signatures. In the report of the technicolor working group[73] two specific such particles predicted by non-minimal technicolor theories are discussed in detail.

A so-called lepto-quark which decays into a quark and a lepton could exist in the 100 to 200 GeV mass range. Such a particle has strong interactions and will be produced in pairs by the gluon-gluon fusion mechanism with a cross-section of order 1 nb. The dominant decay mode is into τ + top quark jet. This case provides an interesting example of a process where it is better to work in a channel which has a small branching ratio but is very clean. The channel selected was μ + top jet. The resolution on the mass of the lepton + jet pair is much better than in the τ case where missing energy is carried off by the ν_τ (compare figures 1 and 2 of ref. 73). It is expected that the background to an event with $\mu^+\mu^-$ + 2 jets is negligible.

The other technicolor state discussed in great detail was the η_{tc}, called P_8^1 by EHLQ. It is a color octet scalar which is produced singly and can decay to a $t\bar{t}$ quark pair. If its mass is around 250 GeV, it will have a production cross-section of order 3 nb.[3] Its detection depends upon rejecting the background from QCD events with two jets and will be discussed below. Suffice it to say here that there does not appear to be a problem.

In some models the techni-baryons will be absolutely stable, in others their lifetimes can be as long as 10^{-10}sec. In either case they will travel for long distances inside the detector.

The production rate of the techni-baryons is difficult to calculate. In contrast to the lighter technipions, they have a size (binding energy) which is comparable to their mass so that production rates calculated on the assumption that they are pointlike are likely to be an overestimate. They can be made in the techni-hadronisation of techni-quark jets, just as protons are produced in the hadronisation of quark jets. This mechanism will operate above the technicolor threshold, and since the production rate involves a convolution with parton luminosities which are falling rapidly with $\sqrt{s}$ most of the production will probably not come from this region. Nevertheless I will assume that this is the relevant mechanism. An alternative mechanism involving the direct production with a form factor suppression is discussed by Errede and Tye[74] who obtain a rate similar to the estimate given here.

The production rate of these particles depends upon whether their techniquark constituents possess QCD color. If they do then they will be produced by gluon-gluon fusion with a rate similar to that of a new quark. In the Farhi-Susskind model there are eight color triplet techiquarks so the total production rate will be eight times that of a heavy quark. The technihadronsiation rate is not calculable; it is the same problem which occurs in QCD when we attempt to calculate the number of baryons in a quark jet. By analogy, it is probably a reasonable assumption to take 0.1 for this techni-hadronisation probability. We then obtain a production rate for technibaryons which is of the same order as that for production of heavy quarks of the same mass.

The possibilities of detecting such quasi-stable objects have been discussed by Errede and Tye[74] who conclude that a few produced events should be sufficient to detect such a stable object and that masses of order 2.5 TeV should be accessible in an SSC run with integrated luminosity of 10^{39}cm^{-2}. They emphasize that the detector must be equipped with a time of flight system if such a quasi-stable particle is to be found.

More work[75] has been done on supersymmetric models than on most other non-standard physics. This has been motivated partly by the theorists recent obsession with it and also by the strange events seen by UA1 collaboration[76] at CERN. These events with jets, missing transverse momentum and no charged leptons are at least superficially similar to those one would expect in supersymmetric theories.

In a supersymmetric theory, the old particles, quarks, leptons, gluons etc., have partners with spin differing by 1/2 unit. Hence squarks ($\tilde{q}$) have spin 0 and gluinos ($\tilde{g}$) have spin 1/2. The masses of these new particles are dependent on the details of specific supersymmetric models but their couplings are fixed. This makes supersymmetric theories especially useful as benchmarks for SSC parameters.

In conventional supersymmetric models the lightest superpartner is absolutely stable. For cosmological reasons this particle probably has to be electrically neutral.[77] It is usually the lightest mass eigenstate in the Higgsino/zino/photino sector. For definiteness the group working on supersymmetry assumed that it was the photino. The production of supersymmetric particles followed by their decay then leads to final states with photinos, which are very weakly interacting and exit the detector. We then have the classic final states of jets + missing transverse momentum.

Supersymmetric models exist where this scenario is not realised and the signatures can become less clear. These possibilities were discussed at the LBL workshop.[78] Most theorists look upon these alternatives with disfavor, but it is important to be aware that they exist. An exhaustive search for supersymmetry at the SSC may have to include them.

Working within the simplest supersymmetric scenario, the supersymmetry group[79] discussed the signals and backgrounds for the supersymmetric final states gluino-gluino, squark-gluino, gluino-photino, and gluino-wino. They even included background estimates from other new physics sources, an important discussion if one is to be certain what new physics has been seen. Table 3 of their report[79] provides a summary.

Using a Monte-Carlo generator a series of cuts on the size and direction of the missing transverse momentum were applied to signal and background events. The ISAJET generator was used. In the case of gluino pair production the final state will consist of $q\bar{q}\tilde{\gamma}q\bar{q}\tilde{\gamma}$ if the gluino is heavier than the squark, resulting in a final state with four jets and missing transverse momentum. Some of these jets will overlap and some may not have enough transverse momentum to be distinguished from the beam fragments. As the mass of the gluino rises, the event rate falls, but the events become cleaner as the jets become more distinct. The main background is from QCD jets which contain a top quark which undergoes a semi-leptonic decay. The opening angle between the missing transverse momentum vector and that of the quark jet from the semi-leptonic decay is limited by the top mass. In addition the presence of a charged lepton can be used as a veto.

The supersymmetry group[79] also considered the effect of event pile up on their signals. Most events will contain jets with only small transverse momenta of order 20 GeV or less (see the earlier discussion concerning jet rates), so an overlap of a few events should not be too serious. The problems caused by pile up are not severe if there are less than 5 events per crossing.

The main conclusions of the supersymmetry group are that the events are rather simple, that there are no insurmountable backgrounds, and that the earlier estimates[3] of the masses of squarks and gluinos which can be probed were too *pessimistic*. The implications for detectors are that hermiticity is exceedingly important, good segmentation is vital (a $D1$[80] type calorimeter with a resolution of 50 mrad in azimuth and .05 units in rapidity was one case used), and that lepton identification is extremely useful as a veto.

Methods which can be used to search for compositeness of quarks and leptons at the SSC have been discussed by several groups.[3,82] The simplest signal for quark compositeness is that of a deviation in the jet cross-section at large transverse momentum which would arise from new interaction terms between quarks of the form[81]

$$\eta_0 \frac{g^2}{\Lambda^2}\bar{q}Aq\bar{q}Aq$$

Here A determines the Dirac structure of this interaction, which depends on the details of the composite model. For definiteness, the form $A = \gamma^\mu(1-\gamma_5)/2$ is used, since the general conclusions are not too dependent on the form. The scale Λ is of order the binding energy of the preons. In EHLQ a criterion is adopted which must be satisfied for a composite effect to be seen. They required that the cross-section $d\sigma/dp_t dy$ should deviate by more than a factor of two from that predicted by QCD, and than there should be at least 50 events per unit of rapidity in a transverse momentum bin of size 100 GeV. A similar criterion was also adopted in a search for an interaction coupling quarks to leptons. In this case, the relevant cross-section is $d\sigma/dM^2$ where M is the invariant mass of the lepton pair.

The effect of detector resolution on the possible compositeness searches is discussed in the report of Albright et al..[83] In the jet case they assumed that the mass resolution on a jet pair was 20 percent. Since the QCD jet pair cross-section falls rapidly with jet pair mass (or transverse momentum), this has the effect of increasing the measured jet cross-section by a factor of order 1.5. There is therefore the potential for confusion with a composite effect. However, the factor of 2 deviation suggested by EHLQ still appears reasonable. A similar conclusion is reached concerning the lepton pair signal when the resolution of a typical detector is taken into account.

An important question concerns the opportunities for distinguishing different forms of the interaction, i.e. the form of A, once evidence for composite structure has been found. An attempt to disentangle the form $A = \gamma^\mu(1-\gamma_5)/2$ from the form $A = \gamma^\mu$, a pure vector interaction was made. The values of Λ were adjusted so that the rates for the jet cross-section agreed at $y = 0$. The angular distribution of the jets, or their rapidity distribution, should now distinguish the two cases. While the rapidity distribution is much different from QCD, the two composite interactions are almost indistinguishable from each other (see figures 2 and 3 of ref. 83). This rather negative conclusion is extremely dissappointing since although the discovery of a compositeness effect alone would be fundamentally important, the disentangling of its structure would be vital.

One hope is that polarized beams could help. In a polarized proton the helicity is carried mostly by the valence quarks so that polarizasation effects will not be important unless processes involving these quarks dominate. For most SSC physics this is not the case, however in the case of a composite effect in the jet cross-section, quark-quark scattering dominates at values of p_t where the effect is apparent.[3,83]

The group[84] looking at methods for searching for new W's and Z's considered in detail the possible limits on their masses which the SSC could set, and considered how the couplings of such a new boson could be extracted if one were found. They confirmed that the previous estimates on the limits[3,85] were reasonable. Detailed investigation of the final states from the leptonic decays of a new W or Z can provide information on the couplings. In the Z case this is easier since both leptons can be measured. In the case of a W, these asymmetries do not enable one to tell the difference between a $V + A$ and a $V - A$ coupling. In order to do this, the polarization of the outgoing charged lepton has to be measured.

The decay into a tau enables this to be done since the momentum distribution of the tau's decay products carries information about its polarization. This is easiest for the decay $\tau \rightarrow \pi\nu$. A detailed analysis was carried out[86] (see figure 2 of ref. 86) with the conclusion that discrimination between $V + A$ and $V - A$ is possible for new W masses of order 3.5 TeV or less.

The decay of a new W could involve a new neutral lepton (N). The properties of N are model dependent. It could live long enough to leave the detector before decaying, or it could decay into other leptons and/or photons. The decays of such an object as well as its implications for the discovery of new gauge bosons are reported in ref. 84.

There was some discussion of the limits which could be obtained on flavor changing neutral currents at the SSC. These neutral currents could be caused by contact interactions which are expected in models in which the quarks and leptons are composite,[69] or they could be due to the exchange of new 'horizontal' gauge bosons.[87] I will discuss only the latter possibility. Suppose that such a horizontal gauge boson exists with couplings to quarks and leptons of the type listed in table 2. For simplicity, I will assume that the couplings are of the V-A type, and that the coupling strength is the same as that of quarks and leptons to the W boson in the Weinberg-Salam model. While this assumption is arbitrary, it does enable a comparison to be made of the different ways of searching for these currents, and the general conclusions drawn from such a comparison are likely to be valid in most models. I shall also neglect all mixing angles and assume that the coupling is full strength to all relevant channels.

Firstly, the new gauge bosons can be searched for directly using the SSC and looking for final states produced by the decay of such a new gauge boson. The production rate of H depends on upon which of the couplings in table 2 exist. If all the quark couplings exist then the production rate will be very similar to that of a new charged W with conventional couplings. The observability depends on the final state. If H can decay into quark pairs only, then it will be very difficult to find. Even if a peak could be seen in the invariant mass of a jet pair, it would be necessary to tag the flavour of the jets to be sure that one had a flavour changing current and hence a final state of say $d\bar{b}$, rather than one of $d\bar{d}$ which would be produced by the decay of a new Z with flavor conserving couplings.

For these reasons the only final states considered at the Workshop[88] were those with two leptons of different types e.g. μe or τe. These channels are essentially background free. The report by Albright et al.,[88] considers the production of H via the channels shown in table 2. The table also shows the limits on the mass of H assuming that 35 (5) events are required in a run of integrated luminosity 10^{40}cm^{-2}.

There are already limits on the mass of H from experiments looking for rare K decays. The non-observation of the decay $K_L^0 \rightarrow e\mu$ with a branching ratio of order 6×10^{-6} limits the mass of the H which mediates the transition $s\bar{d} \rightarrow \mu e$ to be greater than 4.5 TeV.[87] A proposed experiment at BNL[89] claims a sensitivity of 10^{-10} for this branching ratio corresponding to a mass limit of 70 TeV. This and other limits from rare K decays make it unlikely that the SSC will be able to make significant contributions unless the $s\bar{d}$ couplings of H are suppressed for some unknown reason.

If they are suppressed then the SSC will provide information on the couplings to other channels. As well as the method discussed by Albright et al., one can search for rare B decays such as $B \rightarrow \mu e$. The production rate for B's has already been discussed; the report of Cronin. et al.[59] concludes that branching ratios of order 10^{-7} should be reachable for decay channels in which all the secondaries can be detected. One can estimate the branching ratio $B \rightarrow \mu e$,

$$BR(B \rightarrow \mu e) \approx 130 \frac{M_W^4}{M_H^4} \left(\frac{f_B}{.1} \right)^2$$

where I have assumed that the B lifetime is 10^{-12} seconds[90] and f_B is the B decay constant in GeV. Assuming that f_B is order 100 MeV, a value close to most theoretical expectations,[91] values of M_H of 15 TeV or so are reachable.

Other, more exotic, interactions can also be probed using the techniques of Albright et al.[88] For example, the transition $uu \rightarrow \tau^+ \bar{d}$ which violates baryon number is rather weakly constrained from measurements of tau decay. Of course, the process where the tau is replaced by an electron or a muon is very tightly constrained by the limits on the proton's lifetime. In this example the final state will consist of $\tau +$ jet. The rate will be comparable to those for other exotic processes, but there is a background from other final states with W + jet in which the W decays to $\nu + \tau$.

Identification of W's and Heavy Quarks.

Much work was done at the workshop on the question[92] of the identification of final states with W's or Z's in them. Many proposed physics signatures involve the detection of such states. The simplest example concerns the minimal Weinberg-Salam model Higgs boson, which, if heavy enough, is expected to decay into a final state of W^+W^- or ZZ. A Z can always be identified from its leptonic decay modes. Unfortunately this is rather inefficient. Assuming that only the muonic and electronic modes are available, an efficiency factor of 0.0036 is involved. The muonic and electronic branching ratios of the W are larger, but a WW final state probably cannot be reconstructed using them since there are two missing neutrinos in the final state.

The report of Fernandez et al.[92] discusses in great detail how the final state WW can be distinguished from that of W+jet(s). In the case where the W momentum is small, the two jets from $W \rightarrow q\bar{q}$ are widely separated, so that their invariant mass can be well measured. The UA2 group[93] working at the $Sp\bar{p}S$ collider have attempted to detect the W in this manner. Their resolution is at present too poor and the statistics too low for the W to show up. Nevertheless the situation is not hopeless. The better resolution for proposed SSC detectors should improve the situation and it should be possible to detect a slow W.[94]

If the W momentum is very large then the jets from its decay will coalesce. One now has to measure the invariant mass of a single jet. A typical QCD jet of the same energy will tend to have a larger invariant mass and a higher multiplicity. Roughly the probability of a jet of energy E having an invariant mass M is[22]

$$\frac{dN}{d\theta} = 0.25e^{-4\theta}$$

where $\theta = M/E$. At the SSC however is it unlikely that this latter, high momentum, regime can be reached.

Fernandez et al.[92] considered the more difficult case where the W pair have an invariant mass of 1 TeV, a region of critical interest. They require that one W should decay leptonically and that the other decay hadronically. The background now arises from the final state W+jet and is approximately 200 times the signal, so a very strong background rejection is required (compare figures 10 and 11). They find that such a rejection can be obtained by a series of cuts on the mutiplicity, jet mass, distribution of particles within the jet etc.. A realistic detector simulation based on the $D1$ design was used. Figure 12 reproduced from their article shows the reconstructed jet mass from the W, assumed to have a mass of 80 GeV, and a QCD jet of the same energy. A calorimeter segmentation in rapidity of 0.03 units and in azimuth of .03 radians is used. The segmentation of the calorimeter is vital. It is not possible to produce the required rejection if the calorimeter segmentation is 0.1 in both rapidity and azimuth. Segmentations smaller than 0.03 do not significantly improve the situation.

A rejection factor of 200 corresponds to an efficiency of about 25 per cent for the $W \rightarrow q\bar{q}$ mode.[92] I have superimposed on the figure a peak corresponding to the decay of a 90 GeV object. The separation between this peak and the one at 80 GeV gives some idea how well a W could be distinguished from a Z if both decay hadronically. There is clearly some potential for separation.

In view of the large rejection factor obtained, it is reasonable to ask what are the uncertainties in their analysis. Undoubtedly the largest source of uncertainty is in the ISAJET Monte-Carlo which was used to simulate the background. After very strong cuts have been applied, one can become very sensitive to parts of the Monte-Carlo which are not normally tested. The background final state is really W+jets and, as I remarked earlier, the approximation used to generate these multi-jet states is not perfect. In view of the importance of the result, a reanalysis using another Monte-Carlo is probably required.

One question not addressed by Fernandez et al. is whether or not the WW final state can be distinguished from the QCD multi-jet final state if both W's decay hadronically. The signal cross section $d\sigma/dM$ $(pp \rightarrow W^+W^- \rightarrow jets)$ at a W pair invariant mass (M) of 1 TeV is approximately 2.3×10^{-7}nb/GeV, and the background of $pp \rightarrow jet + jet$ is approximately 7×10^{-2}nb/GeV. (See figure 13.) These cross-sections require that the produced particles (W's or jets) be centrally produced, having $|y| \leq 1.5$. These rates then imply that a W/jet rejection factor of order 500 is required. This is larger than that needed when one W decays leptonically. I will assume an efficiency of 0.1 for W detection in this case. (This may be too optimistic, figure 5 of ref. 92 shows a curve of rejection factor vs. efficiency.) Then approximately 0.005 of the W pair events will be detected in their purely hadronic modes, as opposed to 0.06 which can be seen the mode where one W decays hadronically and to other decays either to an electron or a muon.

I will now discuss the ramifications of this very important result. If we require that in the W pair mode 100 detected events are needed in an run of integrated luminosity of $10^{40}\mathrm{cm}^{-2}$, then we can only observe processes with a cross-section of more than 0.16 pb. For the production of a W pair via the decay of minimal Weinberg-Salam Higgs boson, the cross-section is larger than 0.3 pb for all values of the Higgs mass greater than $2M_W$ and less than 1 TeV. This rate corresponds to that where the W's are produced centrally with $|y| \leq 1.5$. If this is relaxed to $|y| \leq 2.5$ the cross-section is always larger than 0.8 pb.[3]

In the case of the minimal techni-rho with $N_{tc} = 4$, the cross-section is approximately 0.06 pb above background for the decay into W^+W^-. There is a larger rate for the combination of neutral and charged techni-rhos which generate final states of WZ and WW of about 0.16 pb above background.[3] The detection efficiency for the WZ final state is reduced since the Z has a smaller leptonic branching ratio; a value of 0.043 instead of 0.06 for the WW case. In this WZ case the final state arising from two leptonic decays can be reconstructed so that the efficiency will increase slightly. The situation is clearly hopeless if experiments are restricted to integrated luminosites of $10^{39}\mathrm{cm}^{-2}$. If N_{tc} is larger than 4 the cross section increases and the techni-rho becomes easier to see. In the case of $N_{tc} = 12$, the cross-section is larger by a factor of 40 or so (see figure 9).

In the case of a strongly interacting W and Z sector, the number of W and Z pair events is comparable to those produced by the decay of a 1 TeV Higgs, and as we have seen the cross-section is large enough for effects to be seen. As discussed above, this physics scenario predicts final states of three or more gauge bosons at a larger rate than predicted by the standard model with a light ($\leq$ 1TeV) Higgs boson. The efficiency for detecting a $3W$ final state is difficult to assess.

A detailed Monte-Carlo study is really required, but I will try to make an educated guess. I will assume that one W decays leptonically into either an electron or a muon, and that the others decay hadronically. The background now arises from final states with W+W+jet(s) and W+ jets. The background rejection factor required is unknown. I will assume that the efficiency in the lepton channel is 1.0 and that in the hadronic channel is 0.25. The fraction of WWW events detected is then 0.017. The efficiency for the other final states with three bosons should not be radically different. This implies that, in order to observe 20 events, 1200 must be produced. If the estimates presented earlier for the production rates are valid, this will require an integrated luminosity of order $10^{41}\mathrm{cm}^{-2}$, which is a seemingly impossible task. Using the same method I can estimate the efficiency for a $4W$ final state where one W decays leptonically to be .004. The same depressing conclusion concerning observability seems unavoidable.

The progress made in designing methods which are able to tag heavy quark jets are reviewed by Ken Lane.[95] Two basic techniques are used. The first relies on the semileptonic decay of the top quark. The electron or muon from a semileptonic decay will have a large transverse momentum relative to the original quark direction, so that the final state will consist of jets and a lepton which is isolated.

Lane and Rohlf[96] considered the effect of requiring one such isolated lepton from a sample of $t\bar{t}$ pairs, and one from a sample of jet pairs produced by quark and gluon final states in the proportions predicted by QCD. For top quark transverse momenta of 100 GeV they obtain a rejection factor of 180 with an efficiency of 0.19. Almost all the semi-leptonic decays passed the cut, whereas the only background jets which survived were those in which a $t\bar{t}$ pair was produced as a fragmentation product in a gluon jet, or those in which the final state of a gluon and a top quark was produced from the scattering of a gluon off a constituent top quark. Both of these rates are rather uncertain, one depends upon Monte-Carlo parameters and the other on the top quark distributions. The methods used for each (ISAJET and the EHLQ structure functions respectively) may be underestimating the effects, and consequently, producing a rejection factor which is too large. As the transverse momentum increases, the leptons become less isolated. At transverse momenta of order 500 GeV the rejection factor falls to 31 and the efficiency to 0.1.

This method suffers from a disadvantage if one is looking at the decay of a particle into a $t\bar{t}$ pair. There is a missing neutrino in the final state so that the particle's mass cannot be reconstructed easily. Only the transverse momentum of the neutrino is measured, Lane and Rohlf assign a longitudinal momentum so that its total momentum vector lies in the same direction as the jet from the top decay. This prescription then improves the invariant mass resolution on the top quark pair.

Lane and Rohlf assigned background to the decay of a heavy particle into $t\bar{t}$ by taking the jet pair cross-section integrated over a range of jet pair masses equal to their resolution in the $t\bar{t}$ channel. They conclude that a particle of mass between 200 and 1000 GeV which decays to $t\bar{t}$ should be detectable in an integrated luminosity of $10^{39}\mathrm{cm}^{-2}$ if its production cross-section times branching ratio is greater than 10 pb.

The second method of tagging t quarks is to exploit the non-leptonic decays. Here the hope is that the fragmentation of a heavy quark is significantly different from that of a light quark or a gluon that a series of cuts will expose it. One such difference is in the momentum distribution of secondaries produced in the fragmentation of a quark.[97] Figure 14 shows a comparison of top and light quark jets at a jet energy of 250 GeV. There will also be differences in the invariant masses of the jets. Hauptman[98] applied a series of cuts to jets simulated using ISAJET and a detector with characteristics similar to those used in the study of W identification. For jets of transverse momentum of order 50 GeV, a rejection factor of 50 is possible with a an efficiency of order 0.15.

These results on top quark identification imply that particles with production rates of greater than 10 pb should be identifiable. So, for example, the η_T predicted in technicolor models should be straightforward to see.[73]

The rates discussed earlier for the production of an intermediate mass Higgs boson in association with a W are less than this. F. Gilman and B. Cox[42], and G. Abrams and B. Cox[99] have carried out a detailed analysis for this case. The t quarks from the decay of a 130 GeV Higgs boson are moving rather slowly so that the jet produced by their fragmentation is not very clear. In contrast, the background from the final state $Wt\bar{b}$ has a clearer jet from the b quark. After cuts a signal to background ratio of 1/6 is obtained.[42,99] Since the top quarks are rather soft, the resolution on the $t\bar{t}$ pair mass depends critically on the ability to detect, and to correctly assign, low transverse momentum hadrons. If the hadrons with $p_t < 1$ GeV are excluded, the peak in the $t\bar{t}$ mass spectrum disappears. The missing energy carried off by neutrinos also spreads the signal. Even if all the soft hadrons are correctly assigned, the effect of detector resolution is to wipe out the peak.[99](See figure 6 of ref. 42.) We are therefore left in the situation of having no method with which we can confidently expect to find a minimal Higgs boson of mass less than $2M_W$.

Conclusions.

I have not discussed the issues relating to fixed target experiments and to the *ep* option. In my opinion, no very strong physics case was made for either of these two options. They should both be regarded as 'second generation' options. In the case of the *ep* option, two different electron energies, 30 GeV and 140 Gev, were discussed. Some cases of physics interest are discussed by J. Gunion.[100]

The general conclusions concerning energy vs. luminosity and the type of incoming beams which were reached earlier[3,101] have not been modified seriously by the results of the Workshop. Chris Quigg[102] reviews these issues in his summary. Some of the earlier studies may have been too pessimistic particularly with respect to searches for supersymmetry. The results on methods for identifying W's and heavy quarks are very encouraging. I will now turn to some outstanding problems.

Where Do We Go From Here?

I will begin by discussing the areas where I believe that more work is clearly required.

The most pressing need is for better Monte-Carlo generators. These generators should incorporate the following features:-

(*a*) They should have all the features of QCD as we currently understand it. Gluon radiation from incoming and outgoing parton lines should be present, and the algorithms should correctly reproduce the growth in multiplicity, jet mass, etc. which are predicted by QCD.

(*b*) Multi-jet final states should be correctly incorporated. The leading pole approximation, which is currently used, is not adequate. In the case of three final states, the QCD calculations are available now.

(*c*) Detailed comparison of the Monte-Carlos with the events from the $Sp\overline{p}S$ collider are required to ensure that those features of the Monte-Carlos which depend upon QCD effects which we cannot calculate are correctly implemented. In particular, the flavor content of jets needs to be investigated more carefully. Many physics signatures rely on identification of top quarks. The background to these signatures can be seriously affected if the Monte-Carlos underestimate the production of top quarks in fragmentation of gluon and light quark jets.

(*d*) It would be extremely useful if Monte-Carlos were available in a user friendly mode, so that if some new physics option opens up it would be very straightforward to add this and look at its consequences in detail.

(*e*) They should be fast. This is probably the most difficult criterion of all, but it is very important. Often the simulation of a background on which strong cuts are to be applied is limited by the number of events which can be generated.

More calculations are required in perturbative QCD. These include the following:-

(*f*) The complete calculation of all the 2 → 4 partonic processes such as $gluon + gluon \to gluon + gluon + gluon + gluon$. These four jet final states can be background to new physics searches. This calculation can then be incorporated into Monte-Carlos so that they can generate the four jet final states properly.

(*g*) The calculation of the rate for the final state $W+$ jet +jet.

(*f*) The calculation of the radiative correction for all the 2 → 2 partonic processes. At present only the corrections for $q_i q_j \to q_i q_j$ are available.[15] This calculation would enable us to determine more accurately the prospects for a detailed QCD test at the SSC, and would also remove some of the ambiguities, such as the choice of Q^2 appearing in $\alpha_s(Q^2)$ and in the distribution functions, which are present in predictions of jet cross-sections.

It is important that the results of these calculations be available in concise analytic forms so that they are readily transportable.

There are some standard model processes which have not yet been calculated. Among these is the rate of production of three gauge bosons. This process should be observable at least when the invariant mass of the three boson system is less than 0.5 TeV or so. Its observation in this region will provide a test of the standard model, but is unlikely to be very interesting unless other failures of the model have already appeared. The region of large invariant mass is important as a background to the three gauge boson states produced by a strongly interacting W system, but, as I have already indicated, the event rates may to be too small to see.

There remains the important problem of finding a minimal Higgs in the mass range below $2M_W$. None of the suggestions appears to stand up to critical analysis. A new idea is needed.

Work is needed on the 'non-standard' supersymmetric models.[78] It is important that the signals discussed for supersymmetry be reanalysed for some of these other models. For example, it is possible that the lightest superpartner is not stable and will decay inside the detector so diluting the classic missing transverse momentum signature.

An 'in depth' study of the usefulness of polarization is needed. Polarization will probably be available at the SSC only if a strong case can be made out in its favor. Prescriptions for generating distribution functions for polarized partons inside polarized protons are available. The simplest prescription is to assume that all the polarization is carried by valence quarks and that the polarized valence quark distributions have the same x dependence as the unpolarized ones. SU(6) symmetry then suffices to fix them. The more sophisticated method of Carlitz and Kaur[103] allows some of the polarization to be transferred to the gluons and sea quarks at larger Q^2. Fortunately, the prescription of Carlitz and Kaur commutes with the Q^2 evolution of the distribution functions[104] so that it is not necessary to evolve in Q^2 using the spin dependent Altarelli-Parisi equations.[4] The prescription can simply be applied to some existing set of distributions. The data from polarized deep inelastic scattering[105] are rather poor, so that some attention will have to be paid to the ambiguities in these distribution functions.

This study of polarization issues should look at all the physics where polarization could be useful; disentangling the structure of an interaction due to the compositeness of quarks; and investigations of the couplings of new W's or Z's are the most obvious areas. The study must include a statement concerning how much polarization is needed for it to be useful. Since the polarization is mainly carried by valence quarks, there is likely to be a minimum luminosity which will be required before the effects can be seen.

More work is required on the identification of heavy quarks W's and Z's. The results of the workshop have been very encouraging, but we must ensure that we are not being fooled by some of our Monte-Carlos. As I have stressed, the efficiency of this identification is crucial, and attempts to improve it are vital.

Very few groups discussed how the detectors may be triggered in the very high luminosity environment. At a luminosity of $10^{32}\text{cm}^{-2}\text{sec}^{-1}$, a simple two jet trigger which requires two jets each with $|y| \leq 2.5$ will have a rate of approximately 10 Hz if the transverse energy is greater than 1 TeV. Some other rates can be found in ref. 102. The supersymmetry group considered the triggering problem and suggested a set of cuts to reduce the rate. A very important issue concerns the compatibility of different triggers. Since the trigger has to be very selective, are we in danger of throwing out one set of new physics while looking for another?

There are a number of 'what if?' scenarios which could affect the physics signatures discussed at the workshop.

What if some new physics is found before the SSC turns on? If this new physics involves particles which do not have strong interactions the the parton distributions are not affected and production rates for other new particles are unlikely to be changed. An exception will occur if a new particle exists which can be produced fairly copiously and can then decay into other new particles. This mechanism could signficantly enhance the production rate of these other new particles. As an example, consider the production of a new heavy lepton (L) and its associated neutrino (N). For simplicity I will assume that the neutrino is massless. The production rate via the Drell-Yan mechanism and a virtual W is shown in figure 15. For an integrated luminosity of $10^{40}\mathrm{cm}^{-2}$ there are 200 or more events if $m_L \leq 1$ TeV. If there exists a new W of mass 4 TeV with the same coupling to quarks and leptons as the existing W, approximately 10000 will be produced for the same integrated luminosity.[3] The branching ratio into LN pairs will be approximately 0.07 if $m_L \leq 3.5$ TeV, so that this new W will act as the primary source for heavy LN pairs.

If this new physics involves the presence of more new strongly interacting particles with masses less than 50 GeV or so, several changes will occur. The proton will contain these heavy particles at small x, just in the same way as it will contain t quarks. If there are few new particles, such as another generation of quarks, then the effects of the distribution functions will be small. In this case, a rough estimate of the distributions for these particles can be obtained from the EHLQ distributions by selecting the one with the mass closest to the new particle, or by interpolating from the masses used by EHLQ. If on the other hand, there are many new species of colored particles, the changes in the distributions could be more drastic.

Suppose that supersymmetric theories turned out to be correct, and that squark and gluino masses were around 50 GeV. The Altarelli-Parisi equations are now modifed.[106,107] Asymptotically the gluon momentum fraction changes from 0.47 to 0.32 and the quark plus antiquark fraction from 0.53 to 0.36. Gluinos carry a fraction 0.08 and squarks 0.24. These changes are quite drastic, but the approach to asymptotia is very slow. Figure 16, extracted from ref. 106, shows the change in these momentum fractions. In generating this figure it was assumed that gluinos were included when $Q^2 > 2500\ \mathrm{GeV}^2$ and that squarks were included when $Q^2 > 4 \times 10^4\ \mathrm{GeV}^2$. The curves are relevant, therefore, if the gluinos (squarks) have mass of order 25(100) GeV. This calculation does not include any mass effects in the Altarelli-Parisi evolutions and consequently, it probably overestimates the effects of squarks and gluinos (see the earlier discussion of heavy quark evolution).

The effects of these squarks and gluinos will be to modify predictions for new particle production. For example, the overall jet rate will not be much affected but the type of jet will change; some will be due to squarks and gluinos. Some jet events will also be unbalanced in transverse momentum. In general the production rates for other new particles should not be too greatly modified. An exception concerns Higgs production rates. Supersymmetric models have at least two Higgs doublets and it is likely that the production rates for one of the neutral Higgs bosons will be larger than in the minimal model.

What if the 'zoo' events seen at CERN[76,108] signal the onset of new physics? The theoretical interpretation of these events was discussed at the Berkeley workshop.[109] Aside from the events[108] attributed to $Z \rightarrow e^+e^-\gamma$ or $Z \rightarrow \mu^+\mu^-\gamma$ most of the events seem to indicate new physics at values of parton-parton center of mass energies around 150 GeV. There is much speculation[110] that supersymmetry may have been discovered, in which case there will be copious production of supersymmetric states at the SSC and the speculation above may be more relevant. If the events are not due to supersymmetry, the consquences are more difficult to assess.

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Tables.

Source	$p\bar{p} \to Z \to e^+e^-$	$p\bar{p} \to W^\pm \to e\nu$
$UA1$	$71 \pm 24 \pm 13$	$530 \pm 80 \pm 90$
$UA2$	$110 \pm 40 \pm 20$	$530 \pm 100 \pm 100$
EHLQ	31	270
EHLQ H.O.	42	363

Table 1. A comparison of the data on W and Z production[7] with the predictions obtained by using set 2 of the EHLQ[3] structure functions. The values are cross-section times branching ratio in picobarns. The entries corresponding to 'EHLQ H. O.' include the higher order QCD corrections.[14] The corrections are reasonably large so it is difficult to assign an error to the theoretical predictions.

Process	35 Events	5 Events
$d\bar{s} + u\bar{c} \to e^- \mu^+$	7.8	11
$d\bar{b} + u\bar{t} \to e^- \tau^+$	6.4	9
$s\bar{b} + c\bar{t} \to \mu^- \tau^+$	3.9	5

Table 2. The limits obtainable[88] at the SSC on the mass (in TeV) of a Horizontal gauge boson which mediates the couplings shown. The limits correspond to the requirement of 35 or 5 events in an integrated luminosity of 10^{40} cm^{-2}.

Figure Captions.

Figure 1. A comparison of the jet data from the $Sp\bar{p}S$ collider[7] with the predictions of the EHLQ structure functions. Shown is $d\sigma/dp_t dy$ for production of jets of transverse momenta p_t at rapidity $y = 0$.

Figure 2. The cross-section for producing a pair of jets each with transverse momentum greater than 10 GeV and with rapidity $|y| < 2.5$.

Figure 3. A double parton scattering which gives rise to a four jet final state.

Figure 4. The gluon-gluon fusion mechanism for new particle production.

Figure 5. The intrinsic mechanism for new particle production.

Figure 6. The development of partonic showers in jet events.

Figure 7. A comparison[23] of the data from UA1[25] with the ISAJET[22] Monte-Carlo. Shown is $dN/d\eta$ for jets of transverse momentum of 35 GeV or more. The jet is centered at $\eta = 0$.

Figure 8. The gluon-gluon fusion mechanism (a) and the WW fusion mechanism (b) for the production of a Higgs boson.

Figure 9. The cross-section for the reaction $pp \rightarrow W^+W^-$ showing the structure due to the techni-rho. The rate is shown as a function of the W pair mass for $N_{tc} = 4, 8, 12$ at $\sqrt{s} = 40$ TeV. Both W's are required to satisfy $|y| < 1.5$.

Figure 10. The cross-section for the reaction $pp \rightarrow W^+W^- + X$ from quark anti-quark annihliation as a function of the the invariant mass of the W pair (M). Both W's are required to satisfy $|y| < 1.5$.

Figure 11. The cross-section for the reaction $pp \rightarrow W^{\pm} +$ jet, summed over the W^+ and W^-, as a function of the the invariant mass of the $W-$jet pair (M). Both the W and the jet are required to satisfy $|y| < 1.5$.

Figure 12. Reconstructed masses of $W \rightarrow q\bar{q}$ and QCD jets produced for W-jet pairs of invariant mass 1 TeV. The W mass is assumed to be 80 GeV, and a calorimeter segmentation of $\Delta y = \Delta\phi = 0.03$ is used.[92] The figure also shows the W peak displaced and centered at 90 GeV, in order to give an indication of the W/Z separation which may be expected.

Figure 13. The cross-section for the reaction $pp \rightarrow$ jet + jet as a function of the the invariant mass of the jet pair (M). Both the jets are required to satisfy $|y| < 1.5$.

Figure 14. Comparison of the rapidity (defined with respect to the jet axis) of hadrons from a light quark jet and a top quark jet.[97] Both jets have an energy of 250 GeV.

Figure 15. The cross-section $d\sigma/dy$ for the reaction $pp \rightarrow L^{\pm}N$ at $y = 0$ where y is the rapidity of the LN pair. N is assumed to be massless.

Figure 16. The momentum fractions carried by quarks (q), gluons (g), squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) as a function of Q^2.[106] The squarks (gluinos) are allowed to contribute for $Q^2 > 4 \times 10^4 (2500)$ GeV^2.

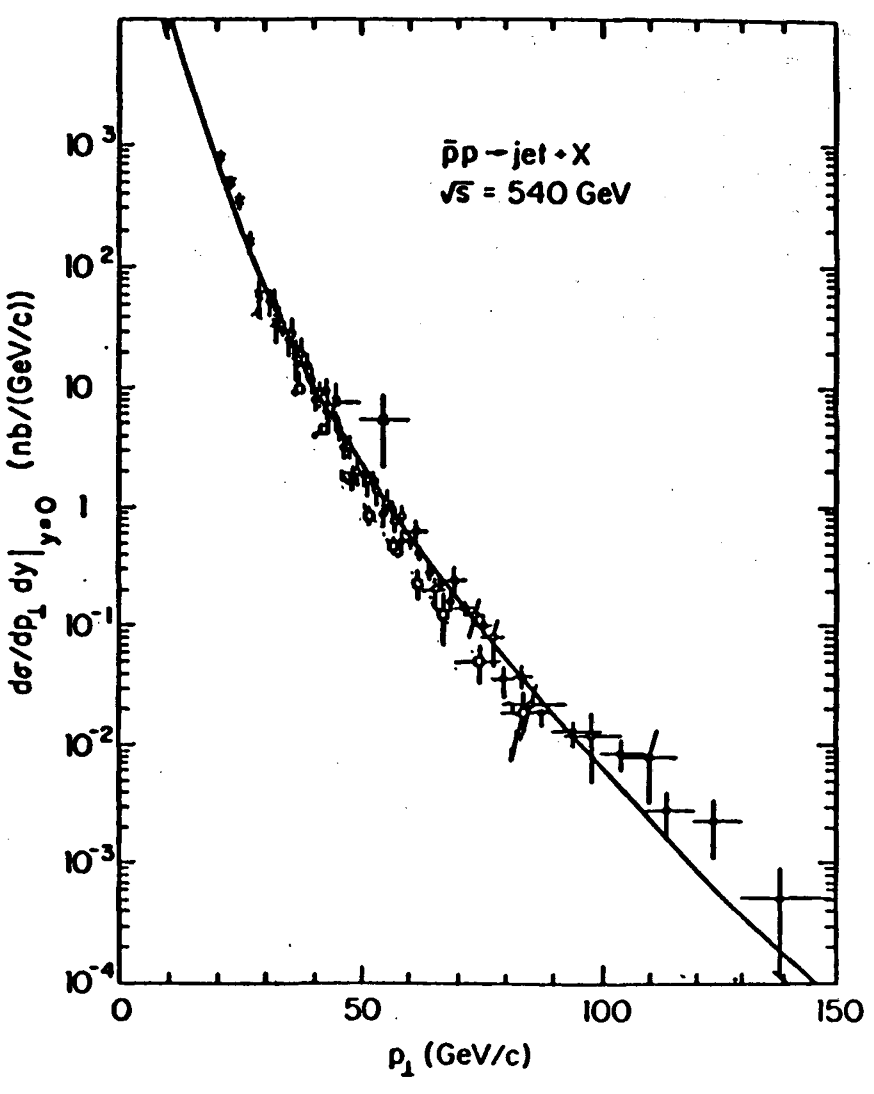
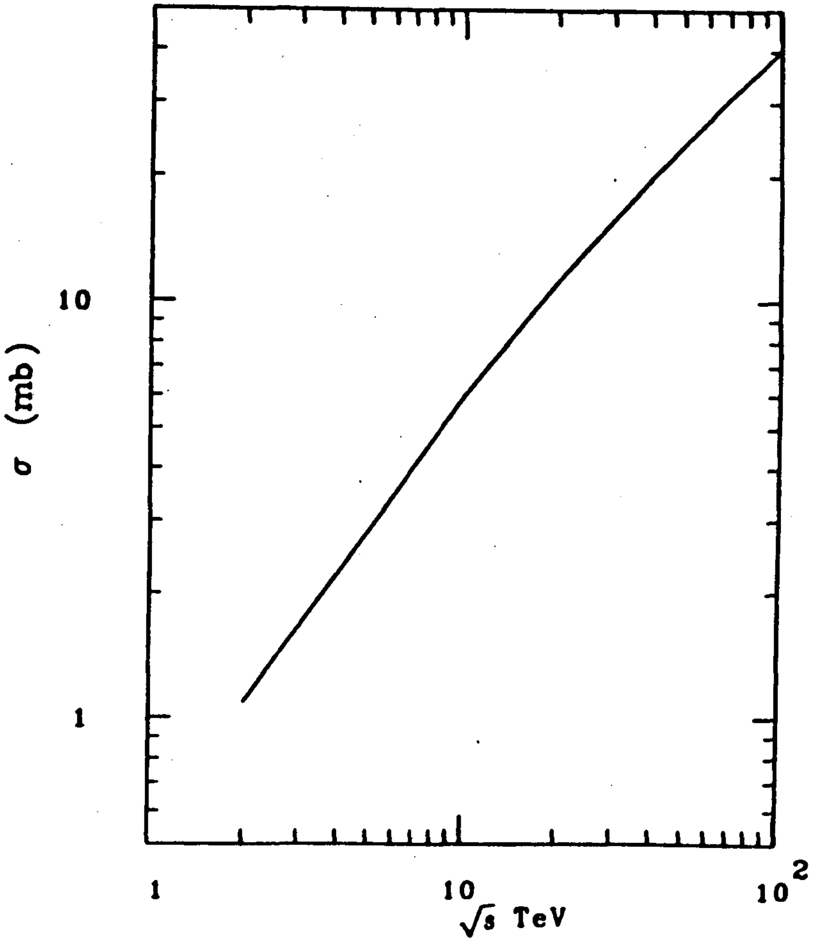


Figure 1



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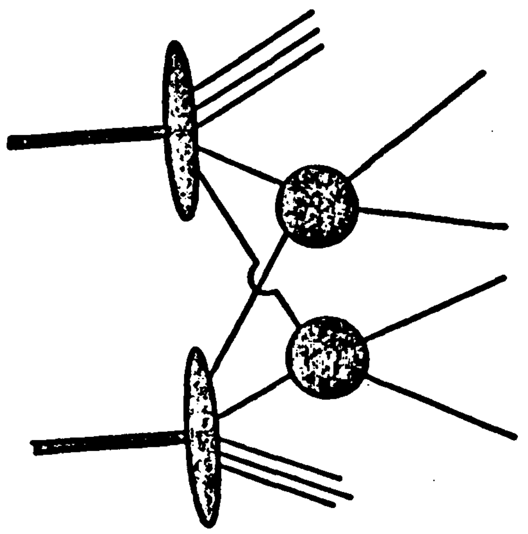

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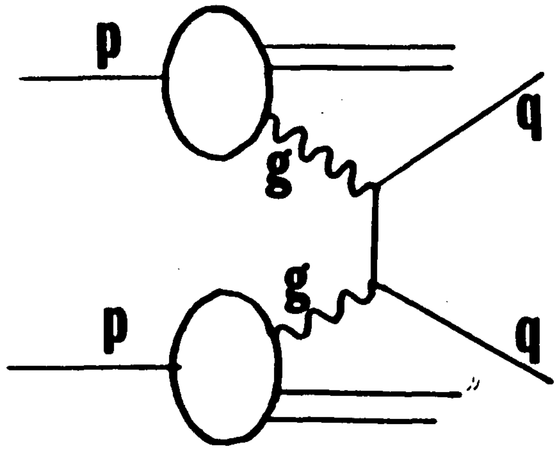

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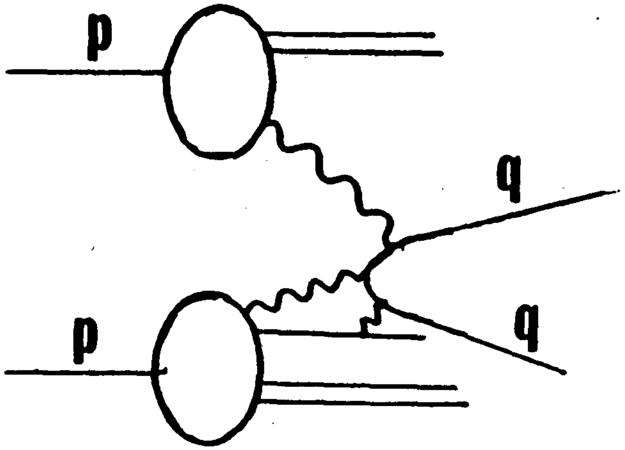

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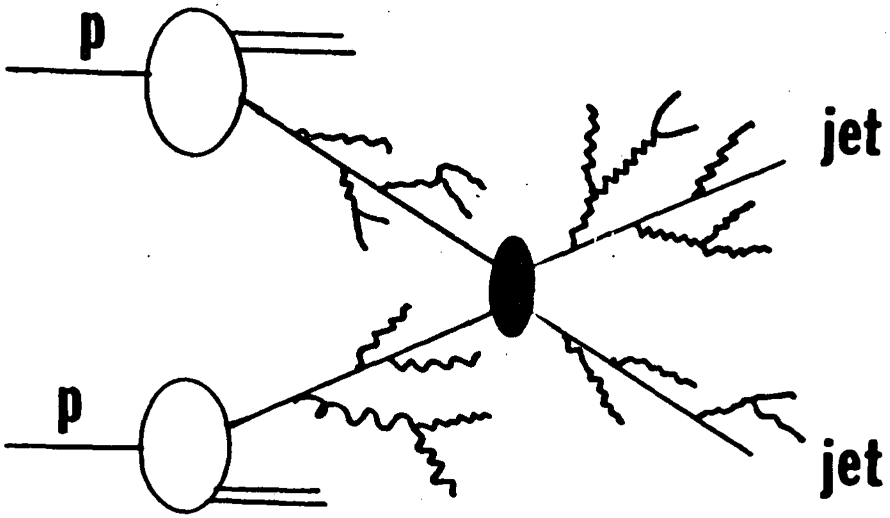

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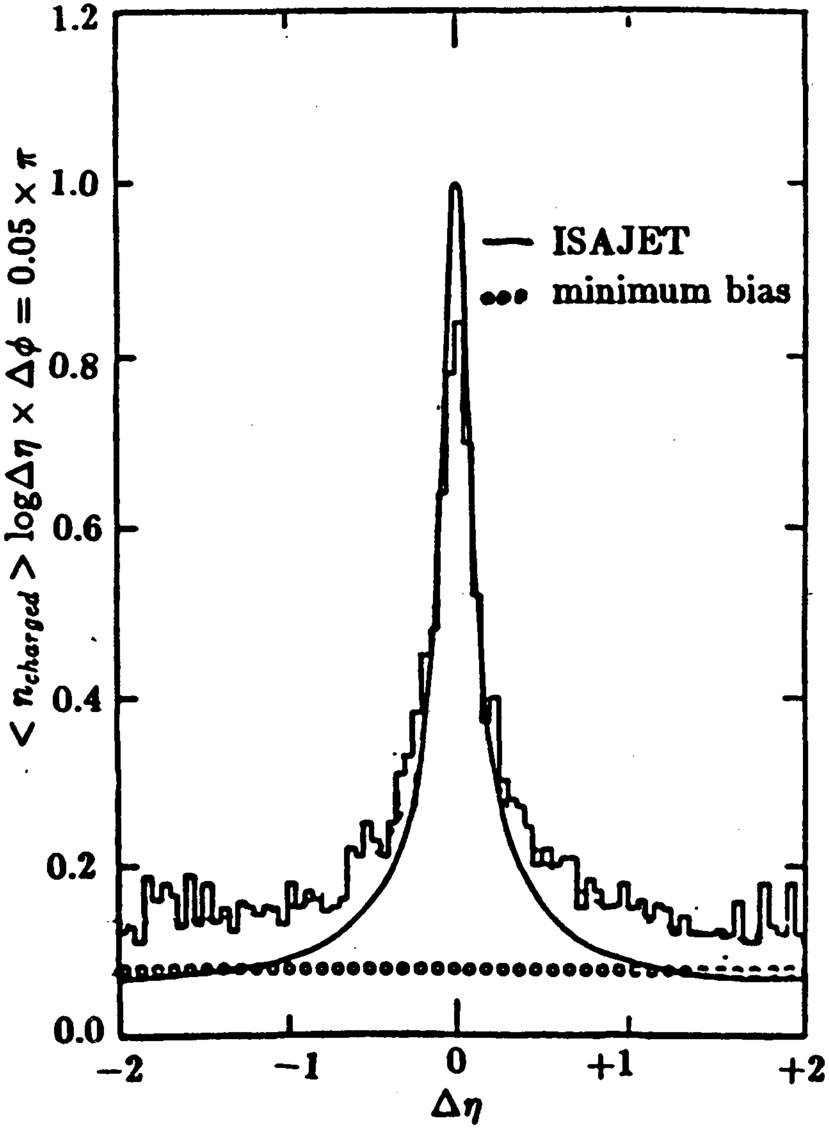

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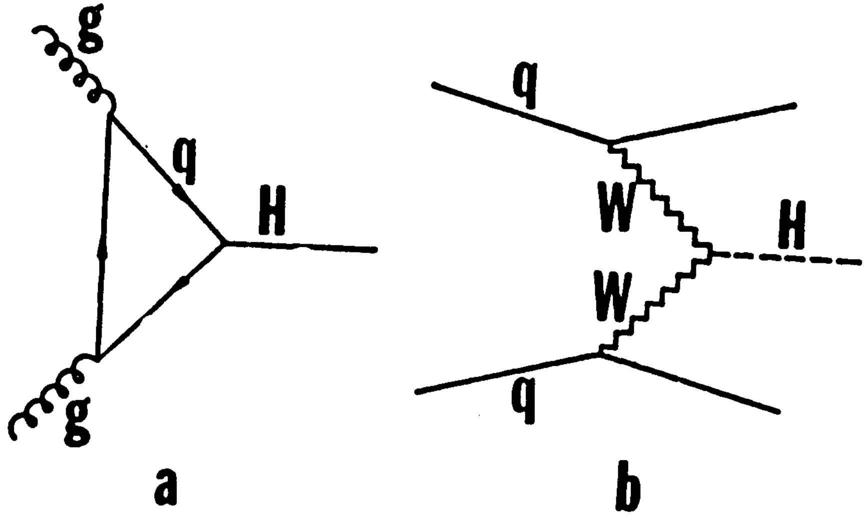

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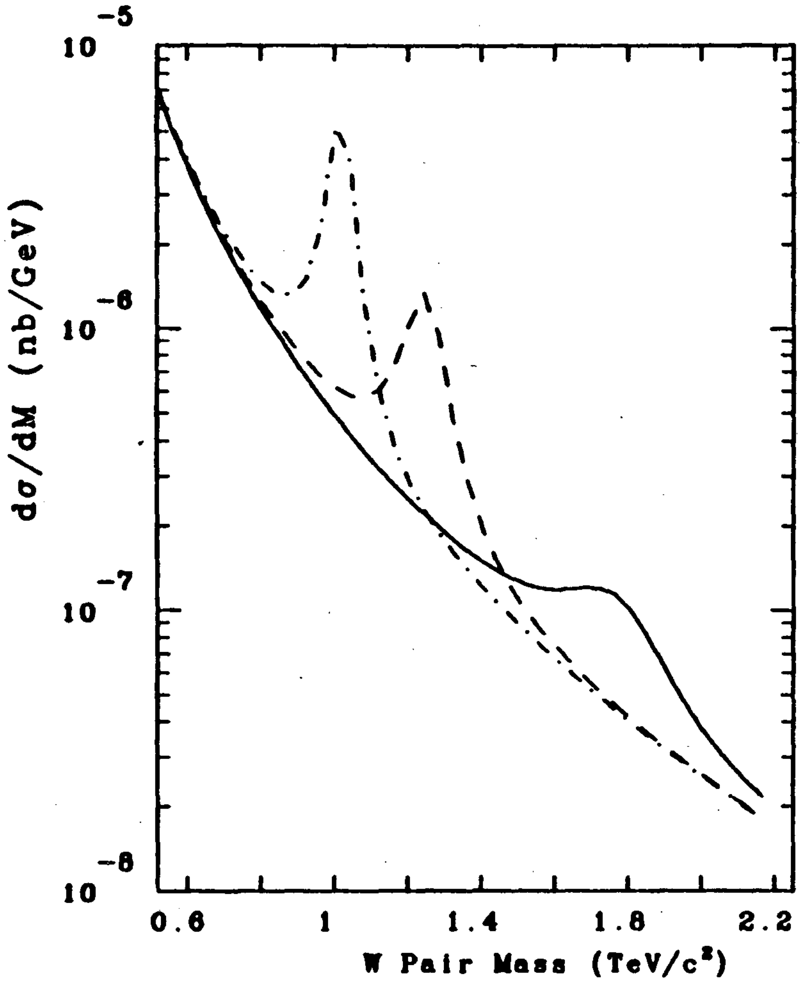


Figure 9

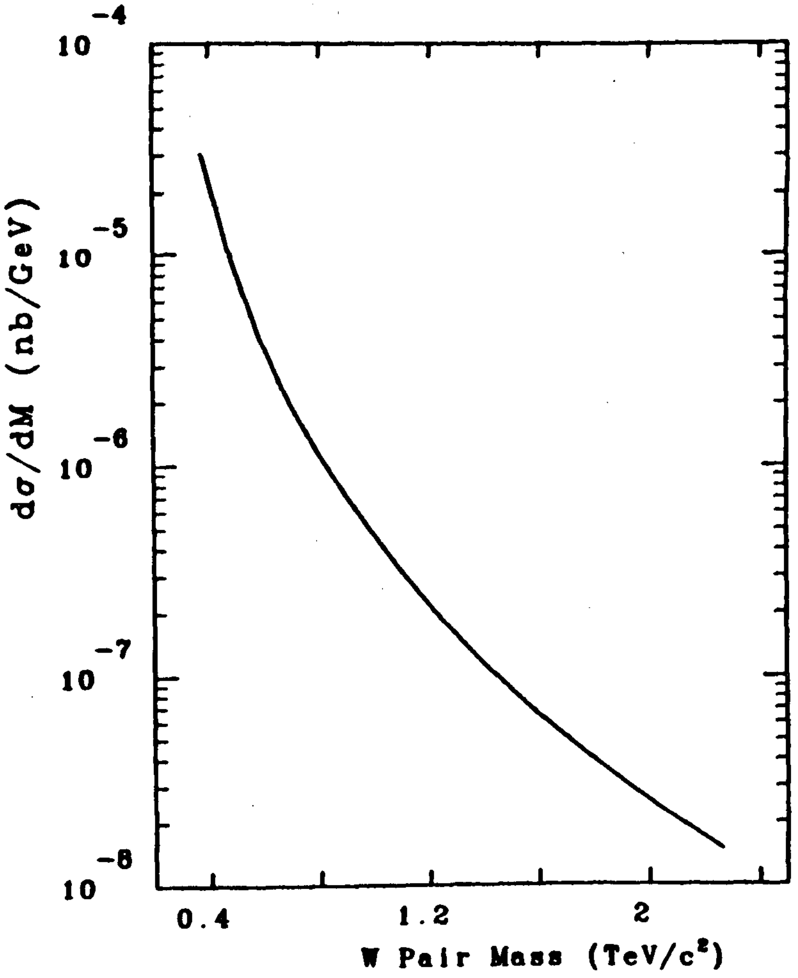
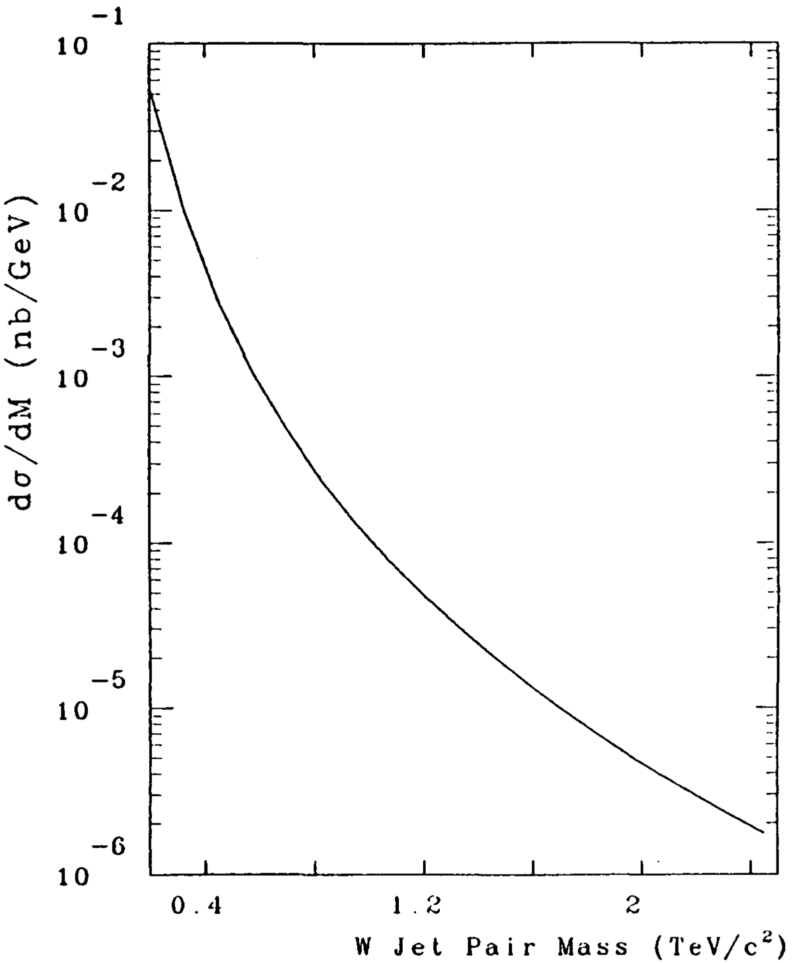


Figure 10



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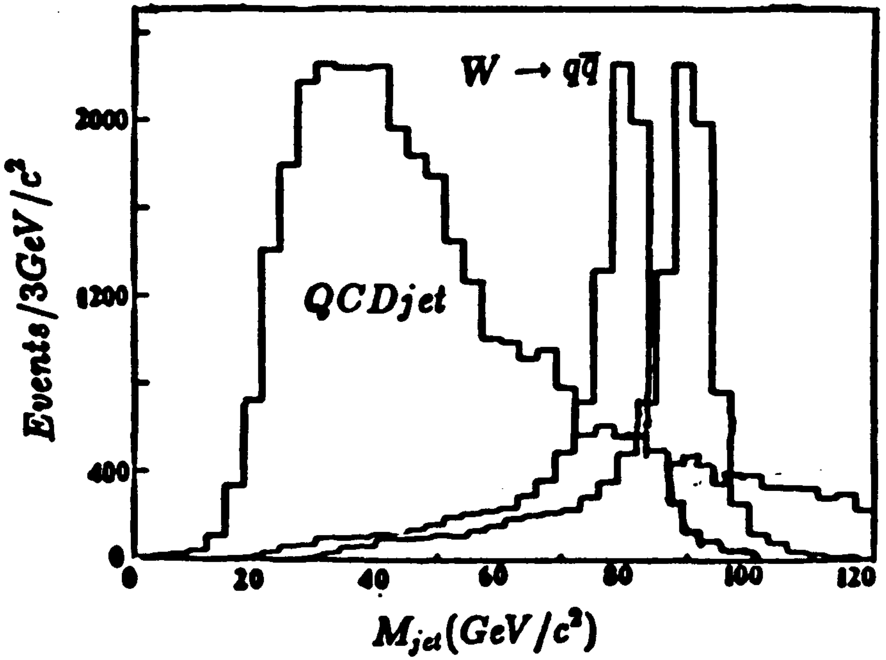

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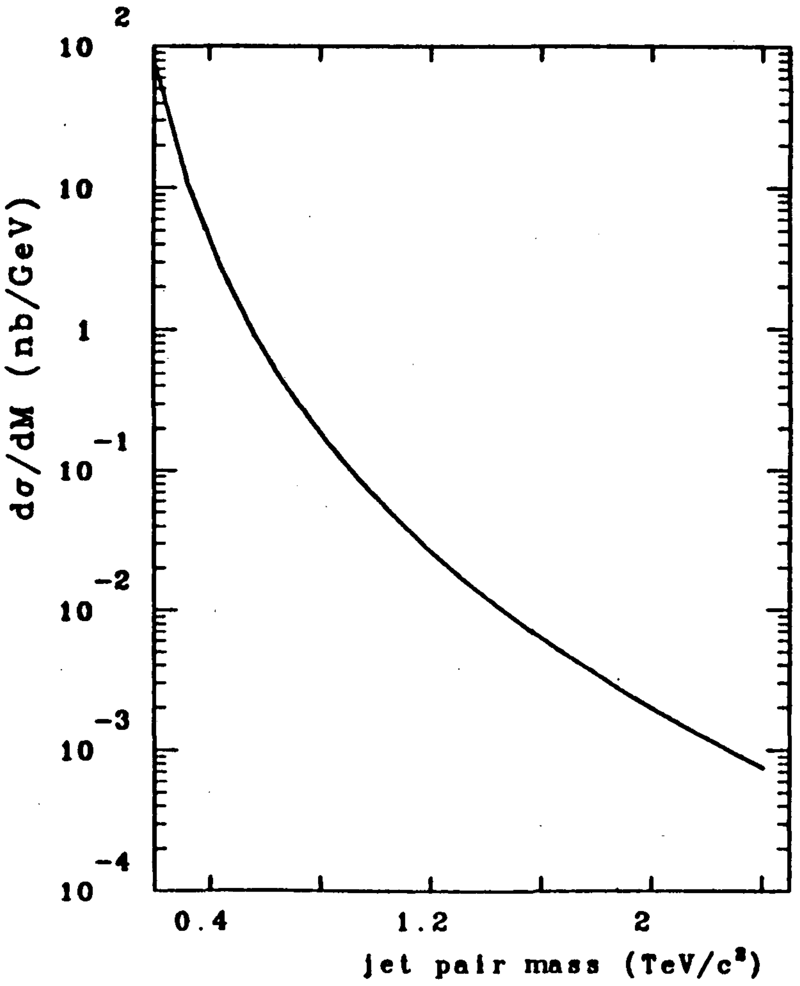
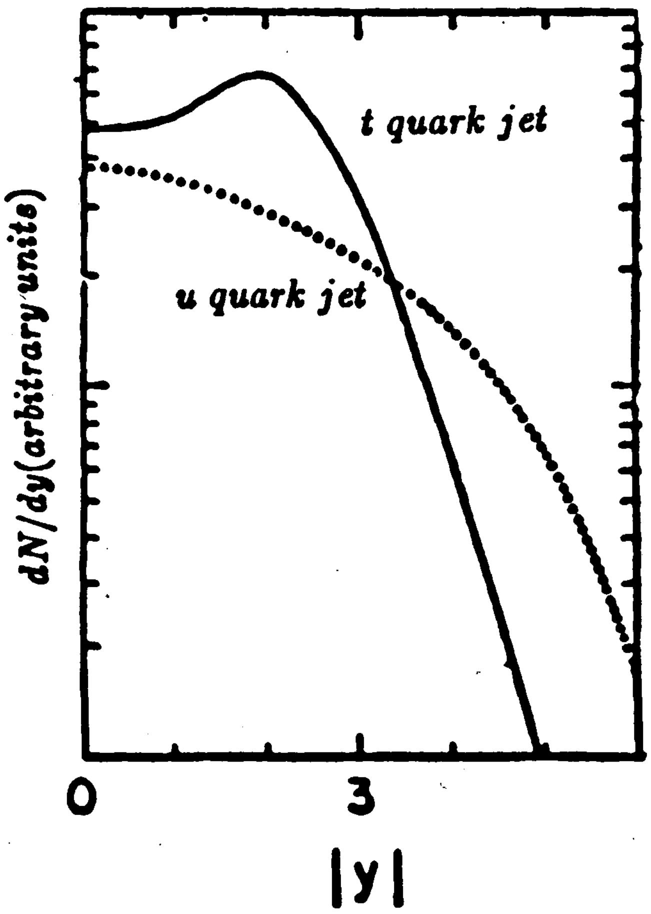


Figure 13



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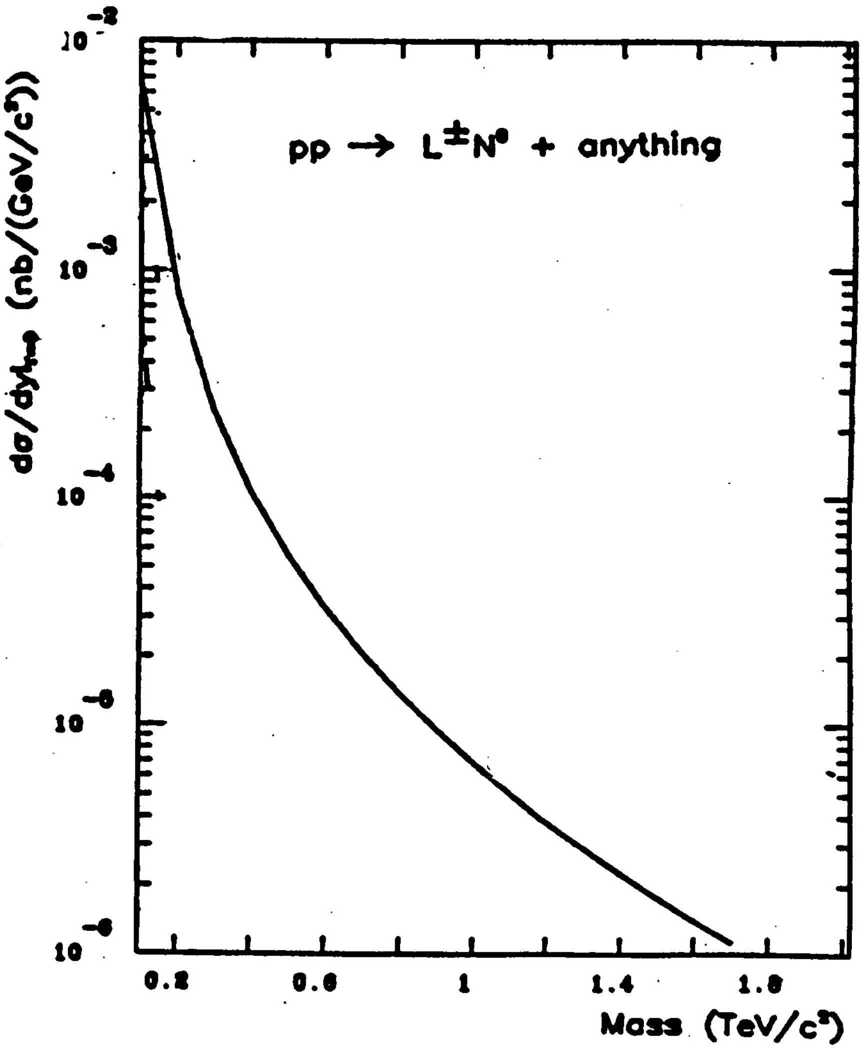

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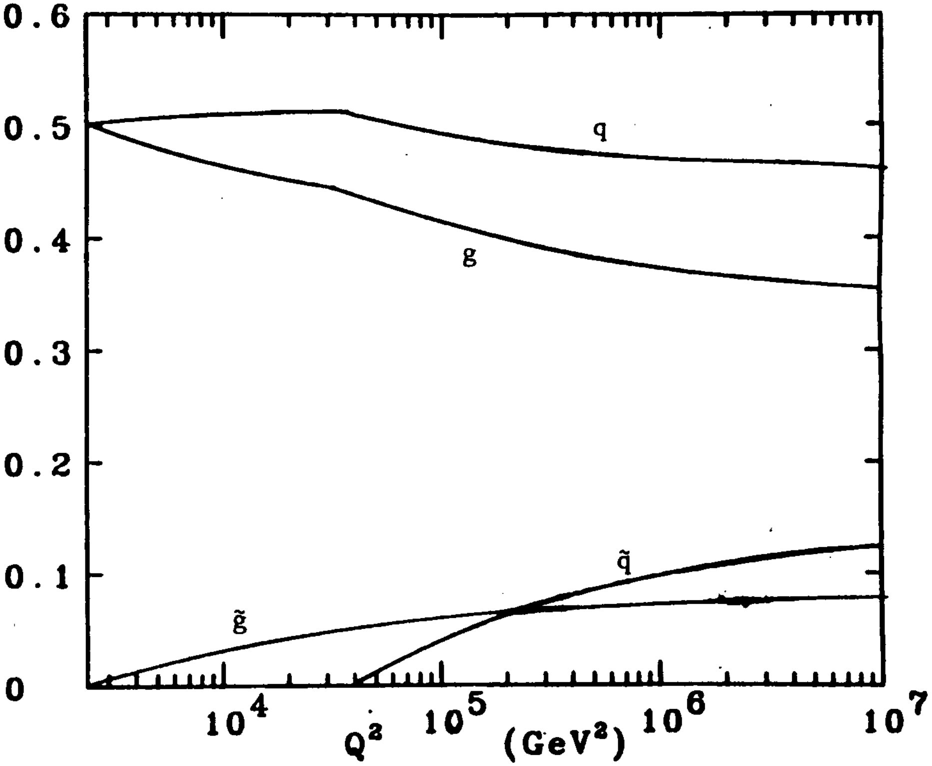

Figure 16

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