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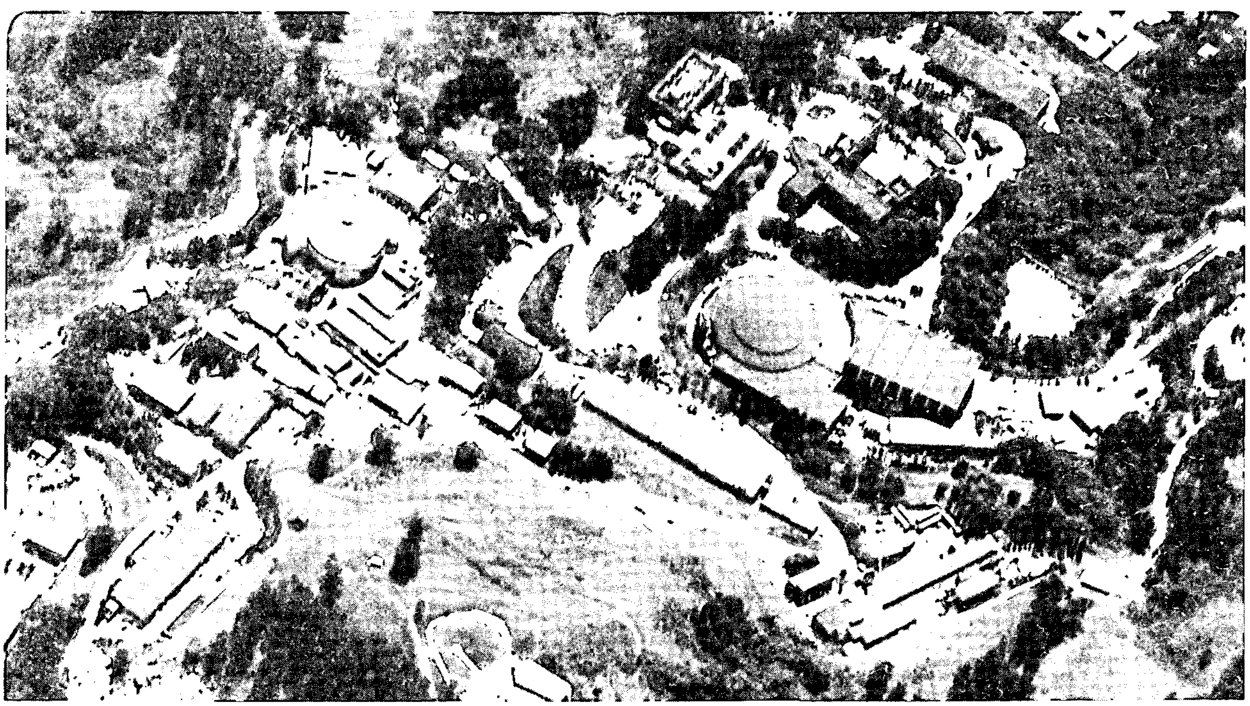
Physics at Large Transverse Momenta

I. Hinchliffe

December 1987



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PHYSICS AT LARGE TRANSVERSE MOMENTA*

(to be included in the Proceedings of the Workshop on Experiments, Detectors and Experimental Areas for the SSC, July 7-17, 1987, Berkeley, CA)

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Abstract

The methods used in estimating the signals and backgrounds involved in searches for new particles at the SSC are reviewed. A brief summary is given of the problems involved in these searches. The required detector parameters are summarized and an indication of the open problems given.

Introduction

At this workshop various working groups were asked to devise strategies for extracting physics signals in the presence of backgrounds and to specify the detector parameters required. Since many people in these groups had considered these problems previously, the conclusions that emerged from the working groups tended to be rather realistic. Generally, groups were conservative in their choices of signal since they were influenced by what they perceived as detector limitations. For example, the heavy quark group required two leptons in their signal because they were concerned about the possibilities for triggering an event with just one. Also, the supersymmetry group made demands for particle tracking since they were skeptical about the hermiticity of calorimeters.

Work necessarily concentrated upon the more difficult signals since these place the most stringent demands upon a detector. The reader will therefore get a very distorted view if she attempts to get an overview of SSC physics from these proceedings. Such surveys[1] have been given ad nauseam, in this workshop it was time to study some hard problems.

Simulating Signals and Backgrounds.

Monte Carlo event generators[2] are used to simulate both the signals and the backgrounds in SSC studies. Two generators (ISAJET[3] and PYTHIA[4]) are used most often. While these generators are very powerful and include simulations of a very large number of processes, they do have limitations. It is important to realise what these limitations are when one is evaluating the conclusions of some physics study for the SSC. The programs should not be treated as black boxes whose output is regarded as holy script. I will make some comments here on some areas where caution should be exercised, and will refer the reader to reviews for more details.

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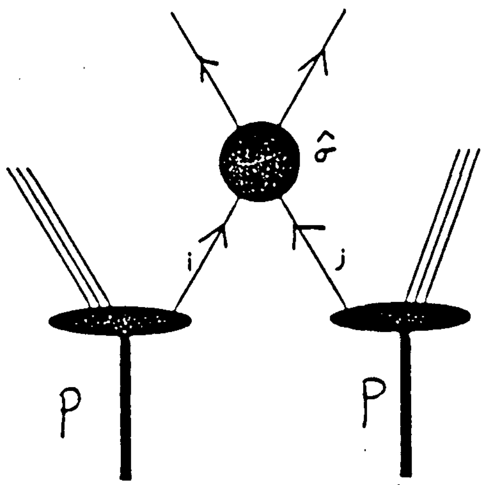

Figure 1: Diagram showing the parton model process $pp \rightarrow jets$.

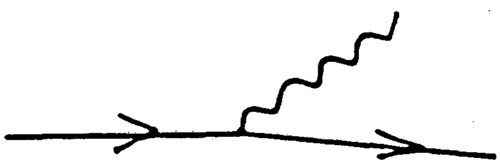

Figure 2: The branching process used to generate initial, or final, state parton showers. This kernel is iterated many times to produce the full shower.

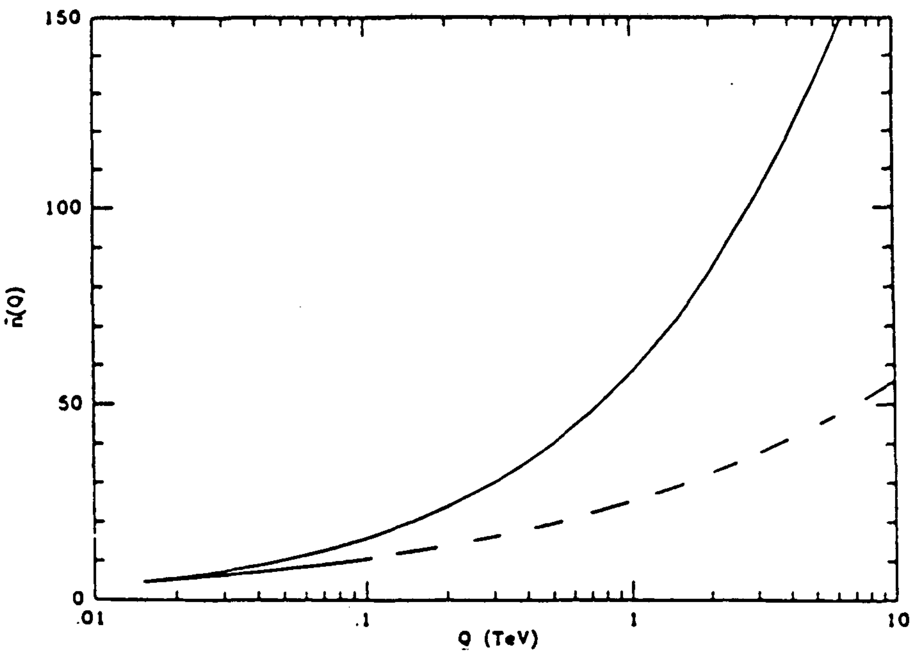

Figure 3: The multiplicity of a quark jet as a function of its transverse momentum. The solid line shows the leading log result, the dashed the result after correction for the coherence effect; figure from reference 9.

The event generators can be thought of as having two almost distinct parts. Firstly, there is the part in which a process is be calculated using perturbative QCD, secondly, the part in which the quarks and gluons of QCD are materialized into hadrons. The first part is, in principle, fully calculable and Monte-Carlo generators are limited only by how well these calculations are implemented. The second part has to rely on parameterization of existing data.

For definiteness, consider the production of some jets at large transverse momentum (p_T) (see figure 1). The parton model divides the process into three stages; † there are the parton distribution functions ($f_i(x, Q^2)$) which are extracted from deep-inelastic scattering data at small Q^2 and then extrapolated up to the scale of order p_T appropriate to the jet process; there is the partonic process which produces outgoing partons at large transverse momenta; and finally the hadronization of these partons into the jets. At lowest order in α_s the parton scattering process is a $2 \rightarrow 2$ scattering which is order α_s^2 and one therefore expects the final state to consist dominantly of two jets.‡ The differential cross section for the production of two jets with rapidities y_1 and y_2 and transverse momentum p_t in the center-of-mass frame of the pp system is given by

$$\frac{d\sigma}{dy_1 dy_2 dp_t} = \frac{2\pi\tau}{\hat{s}} p_t \sum_{i,j} [f_i^a(x_a, M^2) f_j^b(x_b, M^2) \hat{\sigma_{ij}}(\hat{s}, \hat{t}, \hat{u}) \\ + f_j^a(x_a, M^2) f_i^b(x_b, M^2) \hat{\sigma_{ij}}(\hat{s}, \hat{u}, \hat{t})]/(1 + \delta_{i,j}) \tag{3.71}$$

where $\tau = 4p_t^2 cosh^2((y_1 - y_2)/2)/s$. Here $\hat{s}, \hat{t}$ and $\hat{u}$ are the Mandelstam variables for the $2 \rightarrow 2$ partonic scattering. The inclusive jet cross-section calculated by this simple parton model formula is in excellent agreement with the data from the UA1 and UA2 collaborations. However the Monte-Carlo generators attempt to describe the complete event rather than an inclusive distribution.

The structure of a Monte-Carlo generator can be understood from an analogy with QED. Consider the case of $e^+e^- \rightarrow \mu^+\mu^-$. The total rate is given by the simple process $e^+e^- \rightarrow \mu^+\mu^-$ up to corrections of order α_{EM}^3. However, at high energy the final state actually consists of the $\mu^+\mu^-$ pair accompanied by a number of photons which are either soft or collinear with the outgoing muons or the incoming electrons. The final state of $\mu^+\mu^-$ and a hard isolated photon is suppressed by an additional power of α_{EM}.

The dominant final state can be generated as follows. The incoming e^+e^- are allowed to emit photons via a classical branching process shown in figure 2; this constitutes the initial state radiation. The branching kernel for this emission, which is proportional to α_{EM}, is such that the invariant mass of the electron before emission is as small as possible and hence, the emitted photon is either soft or collinear with the electron. After many emissions the electron (and positron) will have an (spacelike) invariant mass of order $\sqrt{s}$. The e^+e^- now annihilate with a cross-section (calculated for on-shell particles) and given by perturbative QED. The outgoing muons now have an (timelike) invariant mass of order $\sqrt{s}$, and now emit photons in the same manner as the electrons so that they eventually have invariant mass equal to

†The derivation of the model from QCD, the so-called factorization theorem, is reviewed by J. Collins and D. Soper.[5]

‡The problems of defining a jet are discussed in the article on Jets and Compositeness[6].

the rest mass when the photon emission stops. This algorithm is correct when the photon is soft or in the leading log (leading pole) approximation where $log(\sqrt{s}/M) >> 1$. This occurs when M, the invariant mass of a photon and its parent lepton, is small; *i.e.* the photons are either soft or collinear with the incoming electrons or outgoing muons. In this region many emissions are allowed since although the kernel is of order α_{EM}, the emission probability contains a factor of $log(\sqrt{s}/M)$.

This algorithm has two main deficiencies. It occasionally will generate a final state with a hard non-collinear photon. This final state is more accurately described by the fundamental process $e^+e^- \rightarrow \mu^+\mu^-\gamma$, with a shower added to each of the initial and final particles. If this process is also added, there is a problem with overcounting since both fundamental processes are capable of populating the same regions of phase space. The algorithm also neglects coherence effects[7] and so overestimates the multiplicity of final state photons. To understand this, consider the emission of a very soft (long wavelength) photon early in the final state shower. Such a photon will really see the charge of the whole final state, which is zero, rather than just that of its parent muon. This emission will therefore be suppressed and the multiplicity of photons reduced.

This basic picture also applies to the Monte-Carlo generators of QCD with some important complications. Leptons and photons are replaced by quarks and gluons which do not appear as physical states. The initial state radiation is responsible for the Q^2 dependence of the structure functions used in the parton calculation.[§] The final state evolution is stopped when the partons are off shell by some value (Λ) of order 1 GeV since $\alpha_s(\Lambda)$ is of order one and QCD perturbation theory ceases to be relevant. At this stage the parton shower is turned into the hadrons seen in the detector. Since this final stage process is non-perturbative, it cannot be calculated. The scale of this hadronization is Λ which does not increase with the jet energy. Data from jets at current energies must be used to parameterize the hadronization. Some features of the events produced by the Monte-Carlo generators are, therefore, dependent upon these parameterizations. If a simulation is sensitive to the details of hadronization, limitations from current data will limit its credibility. The increase in particle multiplicity with jet energy should be due almost entirely to the growth in the size of the parton shower and should be well predicted by the generators.

Data must also be used as input to the parts of the Monte-Carlo that generate the event structure resulting from the beam fragments. This structure consists of low transverse momentum particles. Notice that some of these fragments are due to the initial state radiation, so that the structure of this beam fragmentation event will depend on the hard scattering process. In particular, events with jets will have more low p_T particles than that in events without a hard scattering; this is borne out by data.

The Monte-Carlo generators are able to deal with the coherence effect mentioned above by modifying the shower algorithm, the effect is quite drastic as is shown in figure 3. The problem of higher order corrections is much more difficult. Three jet events will occasionally be produced by the Monte-Carlos when a gluon in one of the showers is emitted at wide angle and with high energy (analogous to the hard photon emission above). However such

[§] In practice the Monte-Carlo generators start with partons off-shell by Q^2 and evolve backwards[8] to generate the incoming shower.

a three jet event is really due, in the partonic language, to an order α_s^3 process of the type *gluon* + *gluon* $\rightarrow$ *gluon* + *gluon* + *gluon*. In the limit where one of the outgoing gluons is either soft or collinear with another one, the event looks like a two jet event. In this region of phase space, the shower algorithm agrees with the order α_s^3 result. The accuracy of this approximation in other regions of phase space has been investigated and found to be accurate to a factor of three or so. None of the existing Monte-Carlo generators include the higher order effects properly. (In the case of e^+e^- annihilation, the problem has been solved[10] at order α_s; here the situation is simpler because there are no colored particles in the initial state.)

It is possible to do some signal/background studies using a partonic calculation that treats the final state quarks and gluons as jets and has no parton showering. In such an approach the fundamental partonic process can be used to the appropriate order in α_s. Since there is no showering and all the outgoing partons are separated, the matching problem present in the Monte-Carlos are absent. Such a simple approach can be used both to suggest areas where more detailed work is required and to dispose of lost-causes. Perhaps more importantly it can be used as a check on the Monte-Carlo's rate for the process in question.

The problem of the observation of a heavy Higgs decaying into W pairs has been analysed in this way.[11] If one W decays leptonically and the other hadronically, the final state consists of a lepton and two jets. There is a background from the production of a W in association with jets when the jets have an invariant mass close to that of the W. The lowest order partonic process which contributes to this background is $W + 2\ Jets$. The relevant partonic calculations are known so a preliminary study can be carried out. The results of such a study can be used to suggest cuts that, when applied to the di-jet invariant mass and the momentum distribution of the two jets which make up the W, which are different for the jets from a real W and those in the background, reduce the potentially enormous background to an acceptable level. A full Monte-Carlo simulation[12] incorporating detector effects can then be undertaken to determine whether these cuts can be used in a real jet environment. Unfortunately, as stated above, the Monte-Carlos use an approximation to the $W + 2\ Jets$ final state, since it is a higher order process. The parton calculation can now plays its other role; it can be used to evaluate the accuracy of the Monte-Carlo's estimate of the background.

We can summarize the main limitations of Monte-Carlos as follows.

1. Higher order QCD corrections are generally not implemented. Hence final states with more than two QCD jets are not correctly generated. The Monte-Carlos will produce events with more jets but the normalization of these rates is not to be trusted to better than a factor of five or so. In some cases, such as the production of three jets the relevant parton cross sections are known and the inclusive jet rates can be calculated in the parton model. Such a calculation can then be used to estimate the credibility of the Monte-Carlo's prediction and possibly to renormalize its event rate. Processes which are limited by this problem include; any final state with more than 2 QCD jets unless some of these jets arise from weak decays, such as the decay of a W boson; production of a W or Z boson at large p_T accompanied by more than 1 jet; events with a two gauge bosons and any jets; and production of a heavy quark-antiquark pair accompanied by more than one jet.

2. Even when some higher order processes are included, they may not be properly normalized. For example, top quarks are produced at lowest order via the processes $gluon + gluon \rightarrow t\bar{t}$ or $quark + antiquark \rightarrow t\bar{t}$. In this case the top quark and antiquark emerge with equal and opposite transverse momenta. The order α_s^3 processes such as $gluon + gluon \rightarrow t\bar{t} + gluon$ can result in an event where the top quark and antiquark have similar p_T and their sum is balanced by the gluon. Both of these processes are included in ISAJET and PHYTHIA. However, the relative importance of these two final states to the total rate for top production cannot be known unless the order α_s^3 corrections to $gluon + gluon \rightarrow t\bar{t}$ are included.[13] These corrections are now known, but are not included in either PYTHIA or ISAJET, hence there is some uncertainty over the interpretation of the rates given by these generators. Again a partonic calculation can be used to check the rates.

3. Some details of hadronization, such as the probability that a jet fragments into a small number of hadrons are limited by available data. For example, occasionally a QCD jet will hadronize into three fast charged particles of low invariant mass and some very soft hadrons which are indistinguishable from those of the underlying event. This "jet" may look like a tau decaying into $a_1(1270) + \nu$. Attempts to use the Monte-Carlos to estimate such "fake" taus may be very unreliable.

4. The branching processes used in Monte-Carlo generators can lead to a loss of information in the following way.[14] Consider the production of a Z pair followed by the decay of both Z's to an e^+e^- pair. There is is an azimuthal correlation of the two planes formed by the e^+e^- pairs. In a Monte-Carlo where the two Z's are produced as on shell particles and then allowed to decay, this correlation is lost. This can have serious consequences if events are generated and cuts on angular distributions made in order to reject backgrounds. This particular example can be dealt with by using the process $q + \bar{q} \rightarrow e^+e^- + e^+e^-$ as the fundamental one. However, in many cases it is not possible or practical (the exact expression can be very complicated and therefore slow to evaluate) to use the full matrix element.

A detailed check of PYTHIA and ISAJET was carried out was carried out by the "Heavy Higgs" group[15] at this meeting. They compared the rates for the production and decay of a Higgs boson and of W and Z pairs given by these Monte-Carlos with the rates predicted by the parton model. In this case the final state particles have no color and the only extra information provided by the Monte-Carlos is in the structure of the underlying event, *i.e.* the effect of the initial state radiation and of the beam remnants. This check revealed several problems with Monte-Carlo generators for these processes even in the cases where only lowest order QCD processes are relevant, most of which have now been corrected. Nevertheless this study contains an important lesson. The generators are very difficult to write and maintain; they cannot be checked too often.

Summary of Physics Signals.

This section provides a brief summary of the physics signals and the required detector parameters. A summary can be found in table 1. In this table, I have attempted to indicate the accessible mass at the SSC and at LHC. These values are a rough guide only, but the same criteria have been used at both energies. Different criteria will result in different values; this usually accounts for any discrepancy between these numbers and those given elsewhere. It is obvious that a higher energy machine has more "reach". A higher luminosity one can compensate, to some extent, for a lower energy at the cost of higher event rate and possibly larger background. Experimentation becomes increasingly difficult at luminosities greater than 10^{33} cm^{-2} sec^{-1}.

Higgs Bosons.

The production rate of a standard Higgs boson is shown in figure 4. The signature depends upon the Higgs mass. It is convenient to distinguish **four** possibilities relevant to the SSC.

First, the standard model is not complete. In this case there may be many scalar (or pseudoscalar) bosons some of which may have electric charge. At this workshop there has been a discussion of the Higgs bosons which occur in the minimal supersymmetric model.[16] The three neutral and one charged particles have production rates which are quite small and signatures which are very difficult to extract. The production rate of the neutral ones at large mass is much smaller than the rate for the standard Higgs boson since the decay width to W pairs is much smaller and the WW fusion process is much less effective. In models of this type there is always one neutral scalar of mass less than M_Z, so detection at LEPII should be possible via the process $e^+e^- \to ZH$. These models also have a large number of supersymmetric particles for which the SSC can search.

A charged Higgs boson can be produced by the process $bg \to tH^-$ or in the decay of a top quark if $M_{H^-} < m_t - m_b$. Its dominant decay is to the heaviest fermion doublet. It is is to be remarked that there is no coupling $H^+ \to W^+Z$. A H^+ of mass 400 GeV is produced in association with a t quark (100 GeV) with a cross section of 10 pb. Its dominant decay to $t\bar{b}$ is likely to be swamped by QCD background. The decay to $\tau\nu$ which has a branching ratio of order 10^{-3} is more promising and is considered in reference 16.

Second, the standard model is correct and the Higgs boson has mass less than $2M_W$. In this case the Higgs will decay dominantly into $F\overline{F}$ where F is the heaviest fermion with mass less than $M_H/2$. If the Higgs is lighter than 90 GeV or so, it will be found at LEPII via the process $e^+e^- \to HZ$. The decay of toponium to Higgs plus gamma may be able to extend this range if toponium exists with a larger mass in the range of LEPII. I shall assume a Higgs mass of 130 GeV in the following but most of my comments are not very sensitive to this choice.

The production rate for a Higgs boson in this mass range is of order 0.1 nb. I shall assume that the Higgs is too light to be able to decay into $t\bar{t}$. The decay $H \to b\bar{b}$ is likely to be almost impossible to see above the large background of $b\bar{b}$ events produced by gluon fusion. There was some hope that the production of a Higgs in association with a W would produce an observable signal.[17] Work done at this meeting has cast serious doubt over this (work by J. Brau reported in reference 18). Semi-leptonic decays of the b quark were used in the analysis which required a lepton with p_t relative to a jet of more than 1 GeV, in an attempt to reject events without a b. A signal to background ratio of order 0.05 was obtained with about 400 signal events passing the cuts. More work is needed but the mode does not

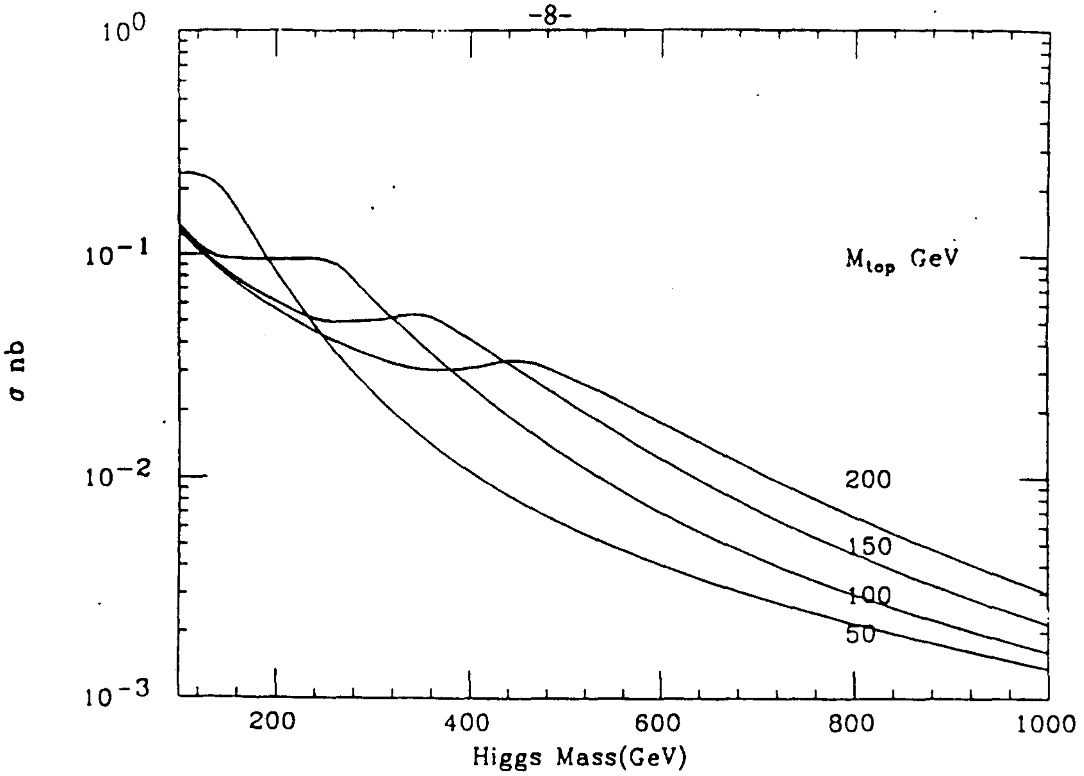

Figure 4: The total production cross-section for a standard model Higgs boson. The lines are labelled with the top quark mass assumed.

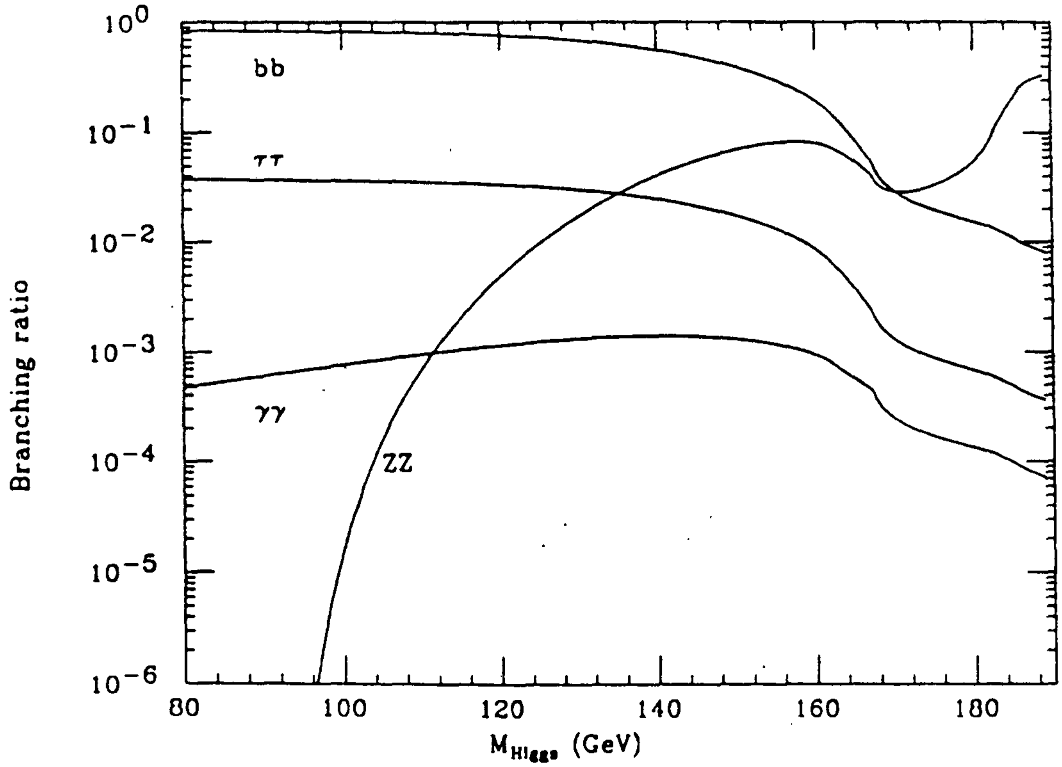

Figure 5: The branching ratios for various decays of the Higgs boson. It has been assumed that $M_H < 2m_t$.

look promising. The main requirement is the ability to detect b's with good efficiency and to reject events with lighter quarks and gluons.

Channels which have a better signal/background ratio are rare decay modes of the Higgs such as $\gamma\gamma$, $\tau\tau$(when the Higgs is produced in association with[19] or without a jet), and ZZ^* (Z^* is a virtual Z, which decays to l^+l^- or $q\bar{q}$). See figure 5 for a comparison of the relevant branching ratios. The first of these is probably the cleanest. The branching ratio is of order 10^{-3}; there are about 300 events/year on a background of about 2500 assuming a resolution of of 2 GeV in the $\gamma\gamma$ invariant mass. (Both γ's are required to have $|y| < 1.5$; this helps to reduce background.) There is also a background from isolated π^0's; attempts to estimate this from Monte-Carlos are limited by current data on jet fragmentation (see above) and are probably not reliable. Since the jet pair cross section is approximately 10^8 larger than the $\gamma\gamma$ one at same energy, a "fake γ" rejection of order 10^4 is needed. Current data on jet fragmentation can be used to estimate whether this is feasible; the problem does not appear to be too serious. Use of this channel requires the ability to trigger, at high efficiency, events with two photons with p_t or order 60 GeV. This is a formidable task.

The second rare process is $H \rightarrow \tau\tau$, which has a larger branching ratio. There is a background from the production of tau pairs via an intermediate Z or photon (Drell-Yan); the method cannot be of use if the Higgs has a mass close to the Z mass. The main problem is the identification of τ's and the reconstruction of their momenta. The presence of a neutrino in the tau decay is a serious handicap since it degrades the resolution in the tau pair invariant mass. By taking the decays of the tau to three or more hadrons the momentum lost in neutrinos is reduced at the cost of a small effective branching ratio. An alternative approach is to require the presence of an extra jet that recoils against the tau pair. In this case the taus' directions can be determined from the their decay products and their total p_t from that of the recoiling jet. The event can then be reconstructed. The problem appears to be that the jet p_t can only be of order 100 GeV if the event rate is not to be too small. Such a low p_t jet is difficult to measure and the resolution is degraded.[18]

The third rare process $H \rightarrow ZZ^* \rightarrow 4$ *charged leptons* has a branching which increases rapidly with the Higgs mass.[20] The Z's can probably only be identified in their decays to e^+e^- or $\mu\mu$ which implies a branching ratio $ZZ \rightarrow 4l$ of 0.0044. This channel will produce 30 or more events (no other cuts) for Higgs masses greater than 130 GeV or so. The background is still under investigation, but does not appear to be serious.[18]

If the $t\bar{t}$ channel is open to Higgs decay, the branching ratio and the signal rate for all the decay modes discussed above is reduced by a factor of m_b^2/m_t^2 which, using the current limit on the top mass, is less than 0.015. In this event all the modes discussed above are seriously compromised.

Third, the Higgs boson has mass between $2M_W$ and 1 TeV or so. In this region it decays dominantly to Z or W pairs. In the former channel the events can be fully reconstructed via the decay of a Z to e^+e^- or $\mu\mu$. This process is rate limited and is effective up to Higgs masses of about 600 GeV. The mode requires the ability to measure μ's and isolated electrons. The presence of two reconstructed Z's implies that the resolution in the lepton pair invariant mass is not critical. At larger masses the mode $H \rightarrow ZZ \rightarrow ll\nu\nu$ may be exploited.[21] Here the signal calls for a single reconstructed Z together with missing transverse momentum.

There is background from $Z + jet(s)$. This background can only be controlled if missing momentum can be well measured. This calls for a hermetic calorimeter with coverage out to rapidity of at least 5.5. At large values of M_H the Higgs is a very broad resonance and no clear peak will be visible. The establishment of a signal is contingent upon the ability to predict (determine) the background.[15]

The Higgs can also decay to WW. The utility of this mode is not yet clear.[12] The ability to detect $H \to WW \to l\nu + jet(s)$ depends on the precision with which the W can be observed in its hadronic decay mode. The background arises from the final states WW and $W + jets$; cuts must be imposed to reject the latter background. The problem is difficult, progress depends on improvement in the Monte-Carlos so that they correctly incorporate the $W + 2jets$ final state (see below) and upon more detailed detector simulations.

If it has large mass, the Higgs is produced in association with two jets that are at large rapidity.[22] The claim[23,24] that these jets would provide a tag to reduce the background has recently been investigated more fully at the partonic level.[25] The tag may help a little but is no panacea. More detailed work involving a full Monte-Carlo simulation is needed. The problems involved in detecting these jets at y = 3-5 and $p_t \lesssim 100$ GeV have not been fully investigated. If this tagging can be utilized, it may also help to reduce the background in the channel $H \to ZZ \to ll\nu\nu$; work is also required to evaluate this.

If the top quark is able to decay into a real W then some of the backgrounds to Higgs searches in this mass range are worsened. The production of $t\bar{t}$ final states leads to a final state with a W pair. For example the total yield of W pairs from a 150 GeV top quark is about 150 times that from $q\bar{q} \to WW$).[26] This is likely to make the process $H \to WW$ very difficult to see even if the $W + jet(s)$ background can be eliminated. This possibility may also compromise the $H \to ZZ \to ll\nu\nu$ mode, at least in the case where $l = \mu$. Chen *et al.*[27] have shown that with a typical iron muon spectrometer, the pair production of a 200 GeV top quark can give rise to a "fake Z" at a large rate. (The presence of two reconstructed Z's in the mode $H \to ZZ \to 4$ *charged leptons* ensures that this mode is not compromised.) A better muon system is then required if the Z decay to muons is to be used.

Fourth, there is no elementary Higgs boson. If the Higgs mass becomes greater than 1 TeV or so, it has a very large width and cannot be thought of as a particle. In this case the couplings of W and Z bosons becomes strong. The signals[28] for such a possibility involve an excess of ZZ, ZW and WW production over that expected from processes such as $q\bar{q} \to WW$ when the gauge boson pair have invariant mass more than 1 TeV or so. Exact predictions for this scenario are not possible, but rates can be estimated fairly reliably.[28] One of the key signals is the appearance of W^+W^+ final states, for which the background is low. To detect this, one must be able to determine the sign of leptons from W decay. The transverse momenta of the leptons extend to 750 GeV. In some models (technicolor)[29] where such strong interactions occur, there are many pseudoscalar particles of mass below 1 TeV that are produced with much larger rates than the gauge boson pairs. The detection of these particles is much easier and will probably be the first indication that such strong interactions occur.

New Gauge Bosons.

These are straightforward to see via the decays $W' \to e(or\mu)\nu$ and $Z' \to e^+e^- or(\mu^+\mu^-)$.[30] There is essentially no background. The leptons in the signal are well isolated. It is of interest to attempt a study of the decay $W' \to \tau\nu$ both as a test of universality and as a method to determine the W' coupling via an observation of the tau polarization.[31] The decay of the tau to a single lepton may be difficult to see. The decay to one or three pions yields a very unusual jet which should be identifiable.

It appears that it will be more difficult for decay $W' \to jets$ than it was for UA2 in their attempt to find the W and Z via their hadronic decay modes at the $Sp\bar{p}S$ collider, since the relative amount of gluons and antiquarks, which control the background and the signal, is larger for the SSC search. There has been some discussion of attempts to detect $Z' \to WW \to l\nu + jets$.[32] Although a Z' is not likely to be discovered via this channel, since $\Gamma(Z' \to WW) \sim \Gamma(Z' \to e^+e^-)$, observation of this channel could be useful to pin down its couplings. As in the Higgs case discussed above, there is a background from the final state $W + jets$. Observation is likely to be challenging.

Heavy Quarks.

A new b' quark that is a member of a fourth generation doublet will decay to Wt. It can be produced in pairs at SSC. The dominant final state will therefore consist of a 6-jet final state, where two pairs of jets reconstruct to the W (assuming that the t quark does not decay into a W). There is expected to be a very large rate for 6-jet events from QCD processes. Existing Monte-Carlos will generate such final state, but they are of unknown reliability (see above). A study at the La Thuile workshop[24] employed a parton calculation that uses an approximation to the 6-jet final state which is better than the leading log one used by Monte-Carlos. They concluded that the 6-jet final state was not useful. However their calculations leave some hope that the channel may be of use at small ($\sim$ 200 GeV) b' masses. However, at these masses, the event rates are so large that other decay modes with smaller branching ratios can be used.

If the t quark can decay into a W the final state will have 4 W's, and the extra constraint may then allow the dominant decay mode to be used. A more detailed investigation of this channel is required since, if it can be exploited, it may provide a better determination of the b''s mass than the method to which I now turn.

A detailed analysis[33] of b' detection carried out at this meeting required that there be two isolated, energetic leptons in the decay of the $b'\bar{b'}$. By selecting events where both leptons come from the decay of the b', and effective trigger can be designed. The hadronic decays of the $\bar{b'}$, which have less missing energy in the form of neutrinos can then be used to determine the b' mass. The background arises dominantly from $t\bar{t}$ production and can be removed by a cut on the transverse momentum of an isolated lepton.

At the La Thuile study[24] and in a paper in these proceedings,[34] the signal and background when only one lepton is required are discussed. In this case backgrounds arise from the final states $t\bar{t}$ and $W + jets$; both can be eliminated by a cut on the leptons transverse momentum.

Signals from the decay of exotic quarks were not discussed at the meeting. In some E_6 based models, there exist charge 1/3 quarks d' which are singlets under $SU(2)_L$. Different decays are possible according to the baryon number assignment of d'. In one case the d' will mix with other down quarks and will then decay $d' \rightarrow Zd$. Pair production will then give a final state with a Z pair and jets for which there is no background. For a discussion of possible decay modes in a supersymmetric theory see reference 35. No detailed detector simulations for these modes have been undertaken, but they are unlikely to have a serious impact on detector requirements.

To summarize, the detection of a new quark will require the ability to measure jets and isolated leptons. It is useful to be able to determine the charge of leptons up to $p_t \sim 750$ GeV. Measurement of missing p_t is not important.

Heavy Leptons.

Consider a 4^{th} generation lepton doublet (L, ν_L). An L^+L^- pair can be produced either via $q\bar{q}$ or gg annihilation. If the ν_L is much lighter than L then the production rate for $L\nu_L$ pairs dominates. L will decay to $W\nu_L$, so that if ν_L is stable, the event will consist of a W at large p_t and missing transverse momentum. The leptonic decay of the W is not observable due to the background from $q\bar{q} \rightarrow e\nu$, which occurs via annihilation through a virtual W.36 The background to the hadronic decay of the W arises from $Z(\rightarrow \nu\nu) + jet(s)$ where the jets fake a W. The claim[24] that the background can be suppressed easily has been refuted by Barger *et al.*[36] who have conducted a detailed calculation of the signals and backgrounds associated with heavy leptons at the SSC. These calculations may be to pessimistic; cuts on the dijet system like those advocated for the similar problem of $H \rightarrow WW \rightarrow e\nu + jets$, can be applied to reduce the background.[37] Nevertheless, the detection of heavy leptons at the SSC will be a formidable task.

Supersymmetry.

Work on Supersymmetry has concentrated upon searches for the gluino ($\tilde{g}$) and squark ($\tilde{q}$). The signals depend strongly upon the decays. In previous studies it was usually assumed that the decays $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ and $\tilde{q} \rightarrow q\tilde{\gamma}$ are dominant. The photino ($\tilde{\gamma}$) leaves the detector without interacting and the classic supersymmetry signal of jets+missing p_t results. It was these decay modes for which the UA1 collaboration searched.[38] In this mode the background arises dominantly from the semileptonic decay of top quarks, which gives rise to neutrinos at large p_t. These background events also have isolated leptons, whose presence can be used as a veto. This decay scenario was discussed in great detail at the La Thuile meeting.[39]

The decay modes are however model dependent. As the squark and gluino masses become larger other modes are likely to dominate. From the point of view of a detector designer, this can have important consequences. For example, the decay $\tilde{g} \rightarrow q\bar{q}\tilde{W}$ ($\tilde{W}$, the Wino, is the supersymmetric partner of the W) which may be dominant, can result in a final state of $W + jets$ after the Wino decays. This final state can be identified via the leptonic decay of the W. The final state now has lepton(s) and less missing p_t. Some of these modes are assessed in detail in these proceedings.[40]

Irrespective of the mode considered the detector requirements are clear. Hermetic calorimetry and detection of isolated leptons (including taus if possible).

Jets and Compositeness.

If quarks are composite it will be revealed in deviations of the jet cross-sections from those predicted by perturbative QCD. Since jet cross-sections fall rapidly with increasing p_t, accurate measurements are contingent upon precise determinations of the jet energies and hence upon excellent calorimetry.[6] If leptons are also composite, deviations in the production cross section for dilepton pairs of large invariant mass can be expected. In this case it will be important to measure these rates accurately. Since the composite interactions may not obey universality, it will be important to measure both electrons and muons (and taus if possible).

Some of the details of jets, for example the growth of the particle multiplicity with the jet p_t are predicted by perturbative QCD. However some of these details are not predicted by QCD and must be parameterized from data (see above). It is very likely that such details will have to be measured at the SSC as a check both of QCD and, more importantly, as a check of the Monte-Carlo programs.[6] Some of the physics signals require rejection of jets at the 10^{-4} level (for example, see the Higgs discussion above); such a rejection is very sensitive to the fine structure of jets. In the measurements of jets, high statistics will be required to check the reliability of such background estimates. These measurements will require a detector which can resolve and measure all the tracks within jets. The measurements will have to be made at various values of p_t from 100 GeV to a few TeV and so cannot be done in a low luminosity interaction region where there will be insufficient events at large p_t. A special purpose detector will be needed for this task.[41] It is not clear whether this can be integrated into one of the 4π detectors.

Summary of detector requirements.

It is remarkable that many of the proposed physics signals at the SSC require similar detection techniques.

Hermetic calorimetry covering $|y| \lesssim 5.5$ is needed for missing p_t measurements required by searches for supersymmetric particles decaying to jets and missing p_t and for searches for the Higgs boson via the decay $H \rightarrow ZZ \rightarrow ll\nu\nu$. There are three main standard model sources of events with missing p_t. The production of a W or Z in association with jets followed by the decay $W \rightarrow l\nu$ or $Z \rightarrow \nu\nu$, see figure 6. In the former case there is an associated charged lepton which is usually isolated. If it is an electron or muon, the event can be tagged and vetoed if necessary. If it is a tau, some of its decays may be easy to pick up. The p_t distribution of the lepton and the neutrino are similar so that the missing p_t can be measured. Of course, the decay $Z \rightarrow e^+e^-$ can be used to normalize the missing p_t due to Z decays. Another primary source is that from the decay of top quarks. This is shown in figure 7. Again the events have an isolated lepton which can be used as a veto. (For an example of this see the Supersymmetry report.) The final source consists of neutrinos from light quarks and particles lost down the beam hole. See Figure 8. These sources are most important at small missing p_t ($\lesssim 200 GeV$). The results from PYTHIA and ISAJET for these distributions are quite differant. This is perhaps not too suprising since they use differant algorithms for generation fo the beam fragments which populate the regions of large rapidity and small p_t.

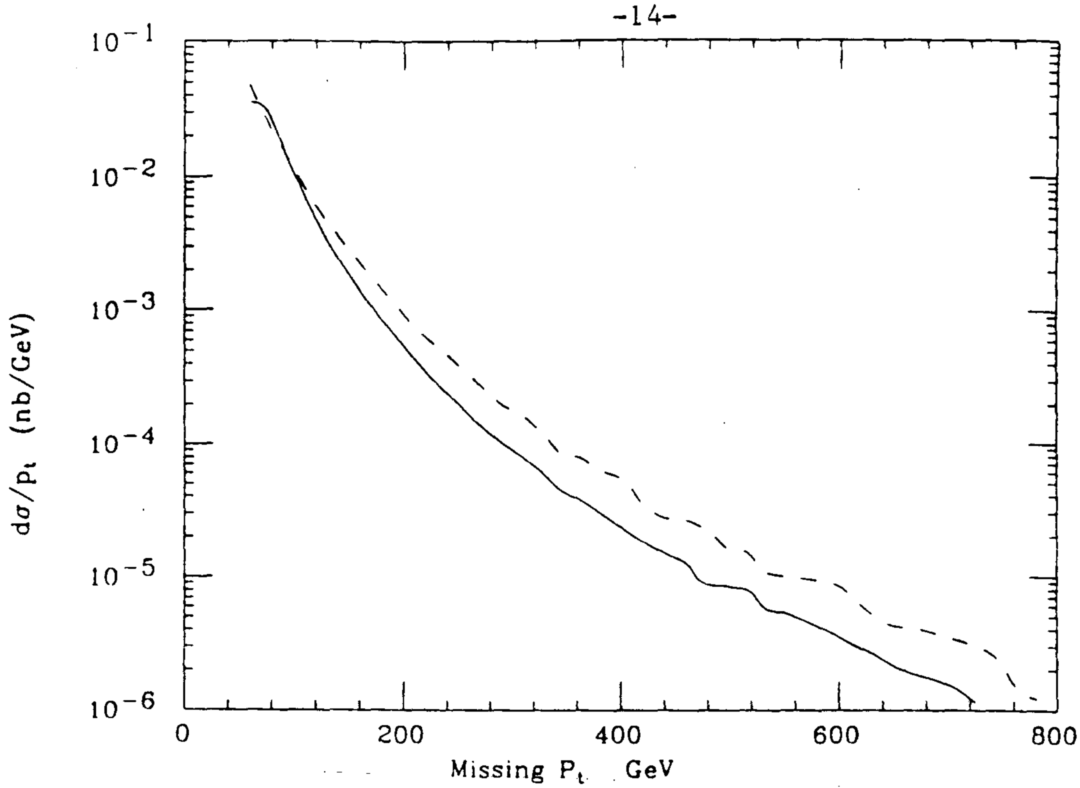

Figure 6: The missing transverse momentum distribution arising from the production and decay of a W (solid line) or Z (dashed line). The missing p_t arises only from the neutrino from $W \rightarrow \nu l$ or $Z \rightarrow \nu\nu$.

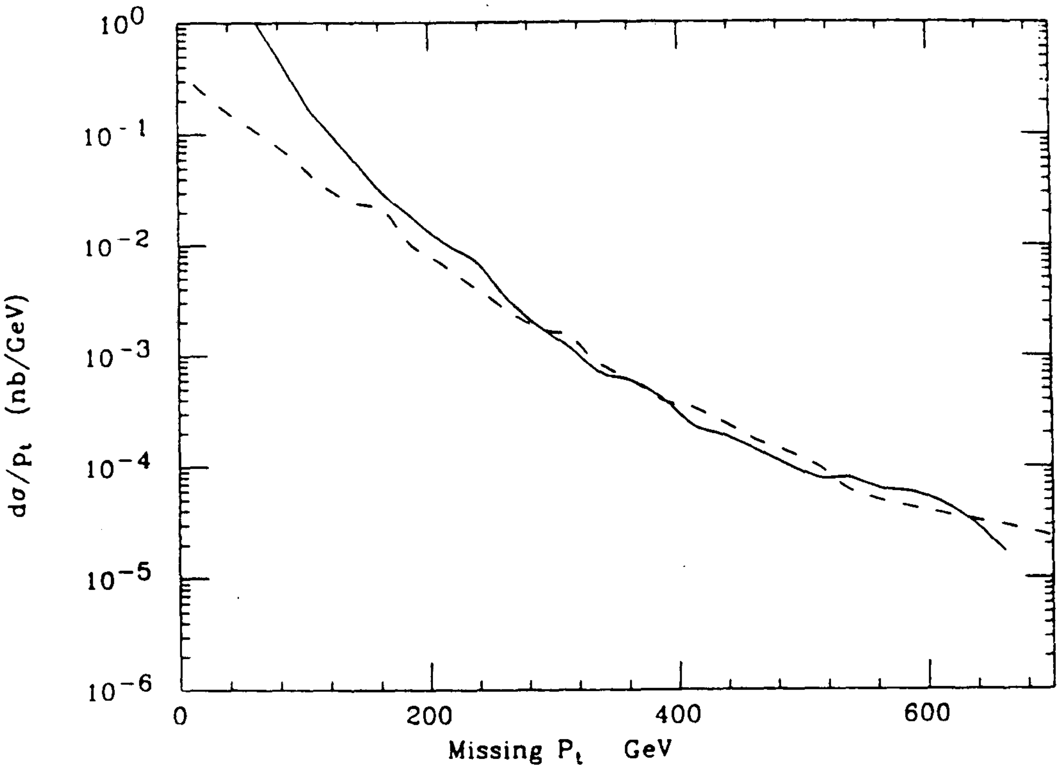

Figure 7: The missing transverse momentum distribution arising from the production and decay of a top quark pair. The missing p_t arises only from neutrinos emitted in the top quark decay chain. The solid (dashed) line corresponds to a top quark mass of 50 (150) GeV.

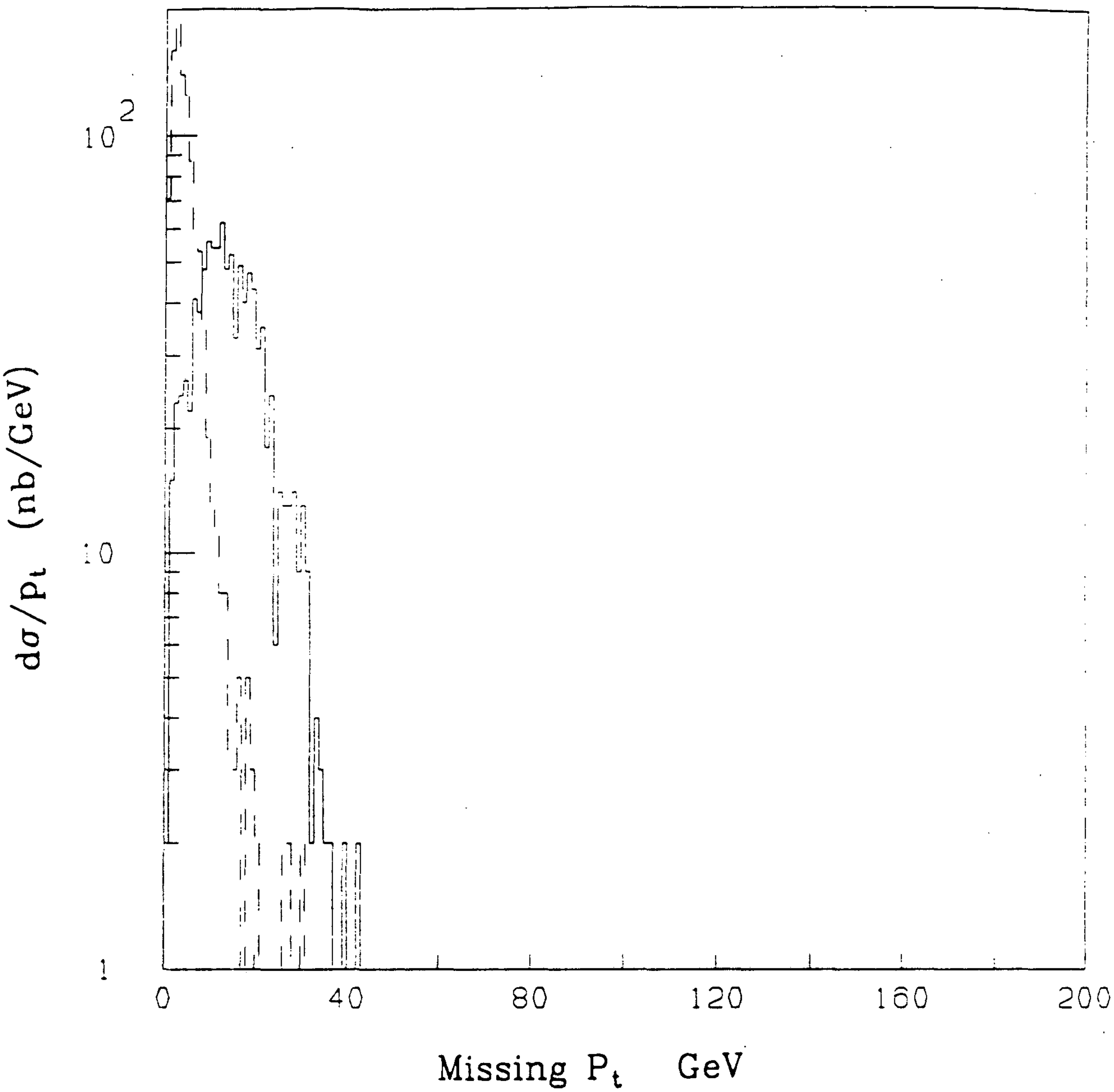

Figure 8: The missing transverse momentum distribution arising from particles with $|y| > 5.5$ which are assumed to be lost. The solid (dashed) line is from ISAJET (PYTHIA). Jet events were generated with p_t of a jet greater than 500 GeV.

Calorimeter segmentation of order $\Delta y \Delta \eta \sim 0.05 \times 0.05$ is needed to study the details of jets and will be important if one hopes to detect the W in its hadronic modes, for example in the processes $Z' \to WW$ or $H \to WW \to l\nu q\bar{q}$.

The ability to identify leptons is vital for many different physics searches. Most of these leptons are isolated from jets and come from Z, W or top decay. The only physics study which asked for the ability to identify leptons close to jets was that which calls for detection of the final state $WH \to Wb\bar{b}$. In this case the event rates are low so that the ability to detect electrons as well as muons is important.

Semi-leptonic decays of light quarks, including bottom, can give rise to hard leptons within jets. The idea that this might be useful to identify b's is mitigated somewhat by the realization that a typical 1 TeV gluon jet contains one $b\bar{b}$ pair and such jets are produced at a rate of 1 Hertz.

Some processes, for example $H \to ZZ \to llll$, benefit greatly from the ability to measure both e's and μ's. Rapidity coverage to $|y| \lesssim 2.5$ is very desirable.

Primary vertex information is important given the large longitudinal spot size of the SSC beam. The only group to consider this problem concluded that a resolution of order 1 cm would be adequate.

Secondary vertex information could be used as a tag for b quarks. While it could be useful for experiments dedicated to studying b quarks, it utility as a tool for new physics searches is limited by the enormous number of b quarks expected in SSC events.

Most of these detector requirements are compatible with each other and are likely to be provided by a good 4π detector. An possible exception is the need for a detector capable of measuring the inner details of a jet. Since there will be ~ 200 particles in a cone of a few degrees, the task is formidable. A detailed assessment of the need for, and design of, such a detector is urgently required.

Unanswered Questions.

Much work on methods for extracting physics at the SSC has been done. There are no substantial disagreements among the various groups who have done careful studies of the same physics. Further significant progress will require a large investment of manpower. So far, no one has taken a designed detector and run simulations on it to determine how well it meets the requirements summarized above. Such a simulation could be valuable, not only for improving the detector design, but also since it may reveal new methods of extracting the signal.

More work is needed on some important areas. In many cases the identification of W's via their hadronic decay modes would greatly simplify extraction of the physics. Taus can also provide a valuable tool, but we do not know how well the 1π and 3π modes can be detected above background. In some areas progress is limited by the Monte-Carlo programs. For example, a detailed evaluation of "tagging" jets at large rapidity in order to improve the $H \to WW$ signal is not possible without a reliable simulation of the $W + 4jets$ background. The appearance of isolated π^0's from the fragmentation of a jet can lead to fake photons. Fragmentation into a three pion system of low invariant mass can fake a tau. The reliability of Monte-Carlo rates for these processes can be improved once more data from the Tevatron become available.

There are some areas where only partonic calculations have been carried out and a more detailed simulation is needed. These include, heavy lepton signals and those from models of strongly interacting $W's$ and Z's.

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