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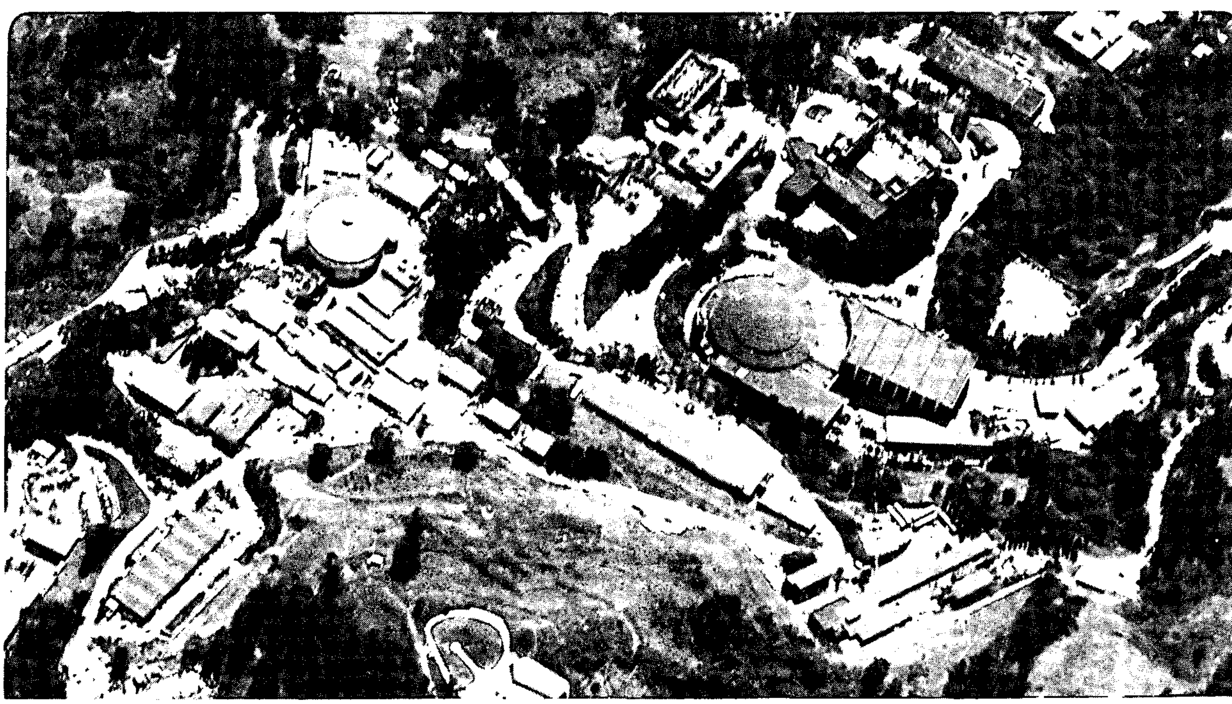
November 1989



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Hadron-Hadron Physics at High Energy and Luminosity *

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Abstract

I review some recent theoretical issues relevant to the physics of hadron-hadron collisions. I discuss processes where either energy or luminosity is the most important feature and emphasize the need for experiments at luminosities of $10^{33} cm^{-2} sec^{1}$ if the full range of physics options is to be thoroughly explored.

Experiments at the next generation of hadron-hadron colliders will fall into two basic groups: first, those that continue the study of phenomena already partially explored, such as the physics of bottom quarks,(1) and second, those that explore a new energy frontier and search for new particles such as a Higgs boson or new massive gauge boson.(2) In the first case, the relevant cross-section grows only logarithmically with the center of mass energy ($\sqrt{s}$). Figure 1 shows the total cross-section for the production of $b\bar{b}$ quark pairs as a function of $\sqrt{s}$ in pp collisions. This cross-section increases by about 50% as $\sqrt{s}$ is increased from 20 to 40 TeV. This figure shows a band of uncertainty in the estimated cross

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section arising from the poor knowledge of the gluon structure function ($g(x, Q^2)$) at small x *and* Q^2. There is an additional uncertainty of order a factor of 2 that arises from the choice of Q^2 scale at which $\alpha_s(Q^2)$ and the gluon structure function is evaluated. These uncertainties are not reduced when the next order ($O(\alpha_s^3)$) terms are included.[3] It is clear from this figure that an increase in luminosity of a factor of 10 is much more valuable than an increase in $\sqrt{s}$ of a factor of 2 for physics processes in this group. Other physics that falls into this group includes the study of any particle whose mass is much smaller than $\sqrt{s}$. For example the study of W bosons at the SSC.

The second group of experiments that involve a search for a new heavy particle are much more sensitive to a change in $\sqrt{s}$. Figure 2 shows the cross section for the production of a new neutral gauge boson (Z') as a function of the Z' mass. This new particle arises in a model where the gauge group of weak interactions is extended from $SU(2)_L \times U(1)_Y$ to $SU(2)_L \times U(1)_Y \times U(1)_\eta$.[4] The couplings of this particle to quarks and leptons determine its production cross section. The Z' would be observed via its decay into an e^+e^- final state. It can be seen from figure 2 that if the mass of the Z' is 4 TeV its production rate is about 20 times larger at $\sqrt{s} = 40$ TeV than it is at 17 TeV.

There is no simple rule of thumb for determining how much an increase in luminosity can compensate for a reduction in $\sqrt{s}$ even for processes that fall into the second group. For processes that are limited by backgrounds rather than by event rates, an increase in energy is usually more valuable than an increase in luminosity. This is because generally signal processes have cross sections that rise more rapidly with $\sqrt{s}$ than do background processes. After these general remarks, I will now discuss some specific physics topics in more detail.

As indicated above, the total cross section for $b\bar{b}$ production rises only slowly with $\sqrt{s}$ and so there is great benefit to be obtained from exploiting the largest possible luminosity. The dominant process contributing to the total $b\bar{b}$ cross section is gluon fusion $gg \to b\bar{b}$. The b and $\bar{b}$ are produced with an average transverse momentum $< p_t > \sim m_b$ and they are close in rapidity. Figure 3 shows the rapidity separation of the b and $\bar{b}$. There is a smaller, though not negligible, cross section for the production of b at large transverse momenta. In this case it is more appropriate to speak of the "fragmentation" of a large p_t jet into a $b\bar{b}$ pair. The b and $\bar{b}$ are now on the same side of a high p_t event, their transverse momenta being balanced by another jet (the dominant process is $gg \to b\bar{b}g$.) Again the b and $\bar{b}$ are close in rapidity (see figure 3). The average number of $b\bar{b}$ pairs in a high energy gluon jet (of transverse momentum p_t) is calculable in perturbative QCD.[5]

$$n = \frac{1}{3\pi}\int_{4m_b^2}^{p_t^2}\frac{dk^2}{k^2}\alpha_s(k^2)(1+2m_b^2/k^2)\sqrt{0.25-m_b^2/k^2} \qquad (1)$$

This is approximately 0.1 for $p_t = 1$ TeV.

In an experiment with an integrated luminosity of $10^{40}\ cm^{-2}$ there will be of order 10^{12} produced b's. The near term goals of a study of bottom is the discovery of the B_s, measurement of its mass and studyof B_s-$\overline{B_s}$ mixing, and the study of some rare decay modes such as $B \to K^*\gamma$.[6] The latter is expected to have a branching ratio of order 10^{-5} in the standard model and may not be out of reach at the current generation of hadron colliders. Recall from figure 1 that the total $b\bar{b}$ cross section is of order 10 μb at the Tevatron. The ultimate goal of all experiments on the b system must be to observe CP violation. This is an extraordinarily difficult task. The classic way is to observe the two charged leptons arising from the semileptonic decay of both the b and $\bar{b}$:

$$\frac{\sigma(B\overline{B} \to l^+l^+) - \sigma(B\overline{B} \to l^-l^-)}{\sigma(B\overline{B} \to l^+l^+) + \sigma(B\overline{B} \to l^-l^-)}$$

This ratio is expected to be of order 10^{-3}. Even if both e and μ are used this will require 10^{10} produced $b\bar{b}$ pairs. Processes that may require less events to see CP violation involve hadronic final states. Of particular interest is the decay of a B^0 or $\overline{B^0}$ meson to some common final state that is a CP eigenstate f. In this case one measures

$$\frac{\Gamma(B^0 \to f) - \Gamma(\overline{B^0} \to f)}{\Gamma(B^0 \to f) + \Gamma(\overline{B^0} \to f)}$$

Since b and $\bar{b}$ quarks are produced in pairs once can use the semileptonic decay of one of them to tell whether the state that decayed to f was B or $\overline{B}$. Two possibilities for f are ψK_S and $\pi^+\pi^-$.[7] Observation of CP violation in this way is likely to require of order 10^8 $b\bar{b}$ pairs.

I will now turn to a discussion of some physics processes that probe the energy frontier. One of the most difficult objects for a hadron-hadron collider to detect is the standard model Higgs boson. Its production cross-section and branching ratio into clean channels results in a very small number of events. While it is true that any self-respecting 4π detector should be able to find a Higgs boson if it exists, it is not true that this particle provides the *raison d'etre* for the SSC. Indeed it is likely that the discovery of a Higgs boson with the couplings expected in the standard model would not enhance our understanding of the weak interaction symmetry breaking.

The Higgs boson is produced via the processes $gg \to H$[8] and $qq \to qqH$.[9] The rate from the former depends on the top quark mass which is now known to be 135 ± 50 GeV.[10,11] Figure 4 shows the total production rate for $\sqrt{s} = 17$ and 40 TeV. Notice that the rate rises rapidly with increasing $\sqrt{s}$ and that the increase is larger at larger values of the Higgs mass.

If the channels are open, the dominant Higgs decay modes are to $t\bar{t}$, WW and ZZ. We have

$$\frac{\Gamma(H \to t\bar{t})}{\Gamma(H \to WW)} = \frac{3}{2} \frac{a_t(1-a_t)^{3/2}}{(1-a_W+3a_W/4)(1-a_W)^{1/2}}$$

$$\frac{\Gamma(H \to ZZ))}{\Gamma(H \to WW)} = \frac{1}{2} \frac{(1-a_Z+3a_Z/4)(1-a_Z)^{1/2}}{(1-a_W+3a_W/4)(1-a_W)^{1/2}}$$

Here $a_i = 4m_i^2/m_H^2$ and $i = W$, Z or t.

The ZZ final state is the simplest to see since the Z bosons can be reconstructed via their decays into e^+e^-, $\mu^+\mu^-$ and possibly $\tau^+\tau^-$. The event rate is very low and acceptance is crucial. If all four leptons are required to have $|y| < y_0$ and $p_t > p_0$, Figure 5 shows the acceptance as a function of p_0 for various values of y_0. It can be seen from this figure that y_0 must be greater than 2 and p_0 less than 50 GeV if reasonable acceptance is to be obtained.

In this channel the background arises from $q\bar{q} \to ZZ$[12] and $gg \to ZZ$[13] and is not overwhelming. Figure 6 shows the distribution in Z pair invariant mass for three Higgs masses. If $m_H \lesssim 700$ GeV there is a clear peak above background so these channels should be useable at $\sqrt{s}$ of 40 TeV and an integrated luminosity of 10^{40} cm^{-2} assuming that both the $\mu^+\mu^-$ and e^+e^- modes can be exploited. It can be seen that the limiting factor is event rate rather than signal to background at $\sqrt{s} = 40$ TeV. This is not true at lower values of $\sqrt{s}$ since, for a Higgs of mass 700 GeV, an increase $\sqrt{s}$ from 10 to 40 TeV the signal rate increases by a factor of 30 while the background only increases by a factor of 5. In this case one cannot compensate completely for lower energy by increasing the luminosity.

If the resolution in the lepton momentum is very poor, there are two potential problems. First, the peak in the ZZ invariant mass distribution is smoothed out. At large Higgs masses the natural width of the Higgs is large and at lower masses the signal to background ratio is quite large so that this effect it not too serious. Second there can be additional sources of background. One possible source is the production of a $Zt\bar{t}$ final state where both the t and $\bar{t}$ decay semileptonically. If the lepton pair from the t and $\bar{t}$ then have an invariant mass that is equal to the Z mass within the resolution, they will constitute an additional background. Estimates of these effects indicate that neither is a serious problem if the leptons are required to be isolated from jets and the lepton momentum resolution is better than 10%.[15]

It has been suggested that an experiment which detected only muons and hence was sensitive only to the $\mu^+\mu^-$ decay mode could run at very high luminosity[16] and so obtain sufficient events to see a signal even at energies much lower than SSC. It is worth remarking that such an experiment has a factor of four less acceptance than an experiment that can detect both electrons and muons. Furthermore, if there is no information other than the muon momentum, it will not be possible to apply an isolation cut and the background (from charm and bottom semileptonic decays) is potentially much larger.

In view of the limited statistics that can be expected in the four charged lepton mode, other modes may be vital to confirm a statistically marginal signal. The mode that has received most attention is $H \to ZZ \to \nu\bar{\nu}l^+l^-$ where l is either e or μ.[17] This has a much larger combined branching ratio. The signal is now a peak in the transverse mass made up from the transverse momentum of the observed Z and the missing transverse momentum. As before, background can arise from $q\bar{q} \to ZZ$ but also from the final state $Z + jets$ where the Z decays to charged leptons and the jets are lost due to cracks or mismeasurement in the detector. This latter process severly constrains the hermiticity required of a detector. As an example, Figure 7 shows the distribution in missing E_t arising from the Higgs decay as well as that arising from the $Z + jets$ final state where the jets are lost down the beam hole. Studies of this type indicate that the detector must be hermetic for $|y| < 4.5$ or better if this mode is to be exploited.[14]

Final states from the Higgs involving the detection of one Z decaying hadronically and the other to charged leptons have a potential much larger signal since the branching ratio is larger.[18] Here the main problem arises from the $Z + jets$ final state where the $jets$ system is indistinguishable from the system that arises from the hadronic decay of a Z. Various cuts on jet mass, event shape and particle multiplicity have been proposed to extract a signal. Many of these depend on details of hadronization of jets and are rather uncertain. While it is not clear that detection of such modes is impossible, I feel that is premature to claim that any of these methods will work.

The decay $H \to WW \to e\nu + jets$ has received considerable attention.[18] This mode may now be unuseable due to the large rate of W pairs arising from the decay of a produced $t\bar{t}$ pair. This rate is approximately 200 (50) times the rate from $q\bar{q} \to WW$ if the top mass is 100 (200) GeV. If the top mass is large, the presence of an additional jets (the bottom quarks from $t \to Wb$) may be used as a veto to reduce this background. Further study of this is needed.

If the Higgs boson has mass less than $2m_Z$ its detection becomes more difficult. Figure 8 shows the branching ratio in this case. (This figure assumes that the top quark is heavy enough so that the decay $H \to t\bar{t}$ is not allowed.) The mode with the best signal to background ratio is ZZ^*:[19] that is the decay to a real and a virtual Z with the subsequent decay to 4 charge leptons. The decay to two photons may also provide a signal provided that the resolution in the diphoton mass is of order 1% and a trigger can be devised.[20]

In the case of some other new physics searches backgrounds are negligible and the search is limited only be the production rate. In these cases an increase in luminosity can always compensate for a decrease in energy provided that the experiment can function at the higher luminosity. The search for a new gauge boson via its decay to e^+e^- or $\mu^+\mu^-$ falls into this category. The discovery of such a particle would be evidence for a real "5^{th} force" and would, in my opinion be more exciting than the discovery of a Higgs boson.

Another example is the search for quark substructure by looking for deviations in the single jet transverse momentum spectrum at large values of p_t. Here one is searching for ad additional to the quark quark scattering amplitude 9in addition to that due to gluon exchange) of the form[21]

$$\frac{1}{\Lambda_*^2}\bar{q}\gamma^\mu q\bar{q}\gamma^\mu q.$$

Figure 9 shows the single jet cross-section at $\sqrt{s}$ of 17 and 40 TeV for values of Λ_* of 15 and 20 TeV.

I would like to conclude this talk with a brief discussion of the physics process that most constrain the various detect or components. The first point is that new physics produces particles that are near rapidity zero. Kinematics forbids the production of a new heavy object at large rapidity. Hence the decay products of these new particles are also located centrally. Recall from Figure 5 that coverage for electrons and muons to $|y| < 2.5$ is probably adequate in the search for a Higgs boson. For processes where a more detailed study is to be carried out, the event rate must be larger, the relevant mass smaller and consequently the rapidity range larger. If a Z' ere discovered with a mass of order 1 TeV then there would be enough events to contemplate measuring the back-forward asymmetry of its decay products with a view to determining the helicity structure of its couplings. In this case coverage of $|y| < 3.5$ will be needed. For much new physics superb resolution will not be required. Such a Z boson will have an intrinsic width of order a few per cent of its mass (recall that the Z has a width of 2.7 GeV). It is important to note that the production cross section is proportional to the width so that a very narrow Z' will have a correspondingly small production cross section.

In the case of new particles that decay to final states involving jets the same comments apply and coverage of $|y| < 3$ should be adequate. Most critical for calorimetric coverage and resolution is the issue of missing transverse momentum. Many of the physics signals require the detection of transverse momentum carried off by neutrinos or other more exotic particles that do not interact in the detector. There are three potential sources of missing transverse momentum that arise in a detector; mismeasurement of jet energies; jets lost in cracks and jets lost down the beam hole. While assessing the impact of detector inadequacies it is important to consider what physics processes produce a background. For example, in the case of the decay chain $H \to ZZ \to e^+e^-\nu\nu$ there is a background from the process $q\overline{q} \to ZZ \to e^+e^-\nu\nu$ and a detector induced background from the final state $Z + jets$ as discussed above. This process is rather special in that the signal has leptons and missing transverse energy but no jets.

Another example that involves missing transverse energy is the search for supersymmetric particles such as a gluino. Here the signal that I will discuss comes from pair production of gluinos, one of which decays directly to a photino (leading to missing transverse energy) and a quark-antiquark pair and the other gluino decays to quark-antiquark, quark-antiquark and a photino. This process which has an overall branching fraction of about 10% can give rise to a final state of up to 6 jets and missing transverse momentum.[22] A jet is defined to be a parton with transverse momentum greater that 50 GeV and a separation from other partons of $\Delta R = \sqrt{((\Delta\eta)^2 + (\Delta\phi)^2)} > 0.7$. Some of these potential jets are lost or merged by this criterion. The final state with the largest rate has three jets in it. There is an irreducible background from the production of a Z boson and 3 jets (where $Z \to \nu\bar{\nu})^{\dagger}$. In addition there is a detector background from the final state with three or more jets where the jet energies are mismeasured or jets are lost down the beam hole or in a crack. The following form was used for the detector's energy resolution:

$$\frac{\sigma}{p} = \frac{B}{\sqrt{E}}$$

To account for cracks which degrade resolution B is taken to be a function of y. Two cracks centered at $|y| = 1.775$ and at 3.025. The factor B above was modified such that $B \to B + 0.7$ at $|\eta| = 1.775$ and 3.025, and fell linearly 0.4 at a distance of 0.125 (in y) on either side of the center position. Figure 10 shows the missing E_t spectrum for the gluino pairs, $Z + jets$, and mismeasurement. It can be seen that the dominant background arises from the $Z + jets$ final state and that improving the detector resolution will not help in extracting a signal.

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[†] There are other possible backgrounds such as the production of a W and three jets followed by the decay of the W to $\tau\nu$ or the production of $t\bar{t}$+ *jets* where one t decays hadronically and the other decays to $b\tau\nu$.

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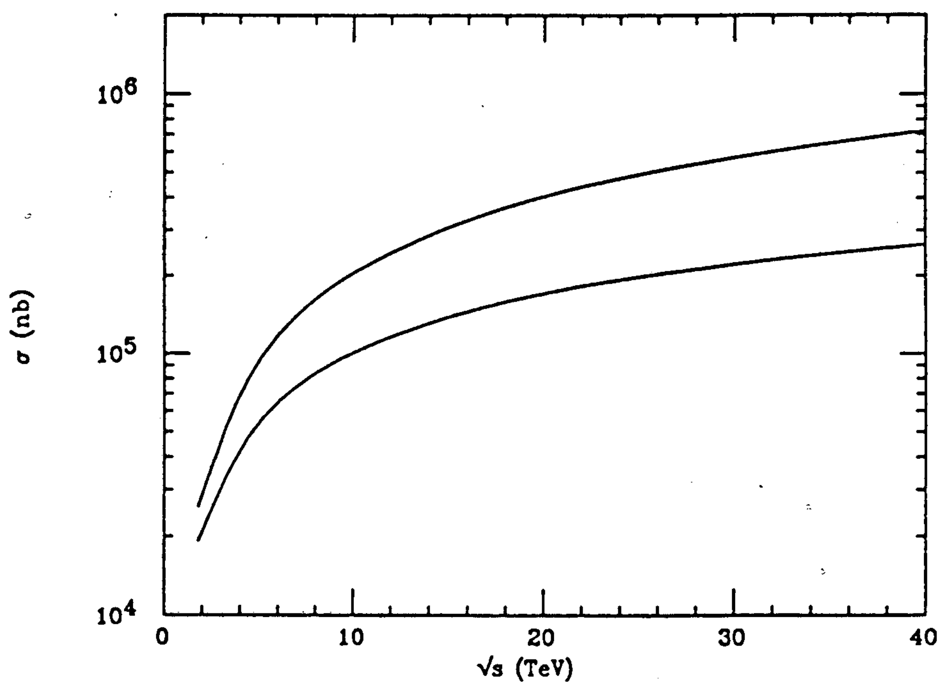

Figure 1. The total cross section for the process $pp \rightarrow b\bar{b} + anything$ as a function of $\sqrt{s}$. The band shows an estimate of the uncertainty in the cross section arising from the poor knowledge of the gluon structure function ($g(x, Q^2)$) at small x *and* Q^2.

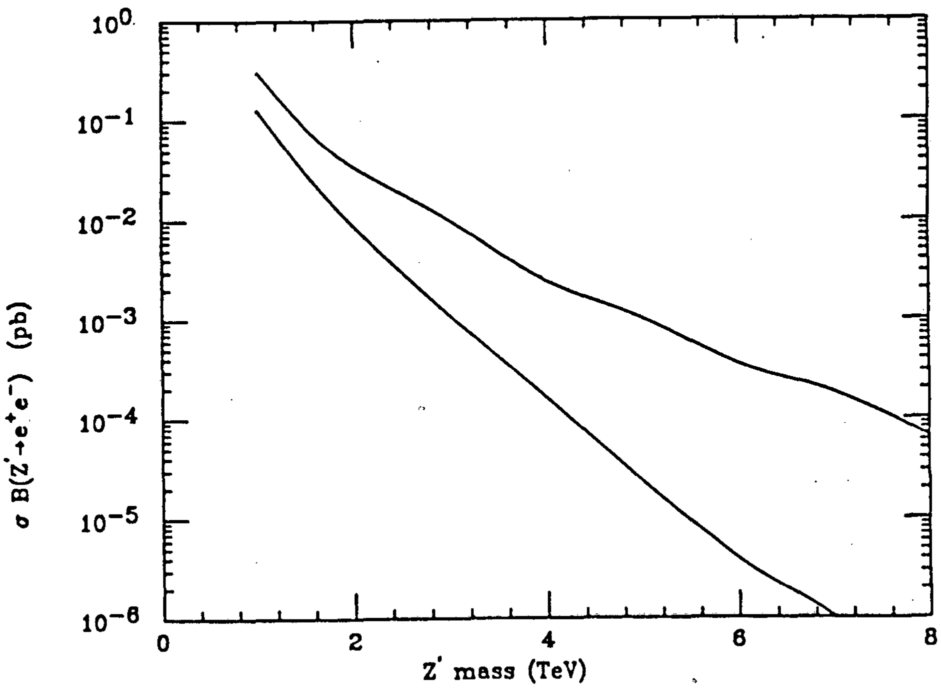

Figure 2. The cross section times branching ratio for the production of a new neutral gauge boson Z' in pp collisions at $\sqrt{s}$ =40 TeV (upper line) and 17 TeV (lower line) followed by its decay to e^+e^- as a function of the mass of the Z'. The couplings of the Z' to quarks and leptons are those of the $SU(2)_L \times U(1)_Y \times U(1)_\eta$ model.

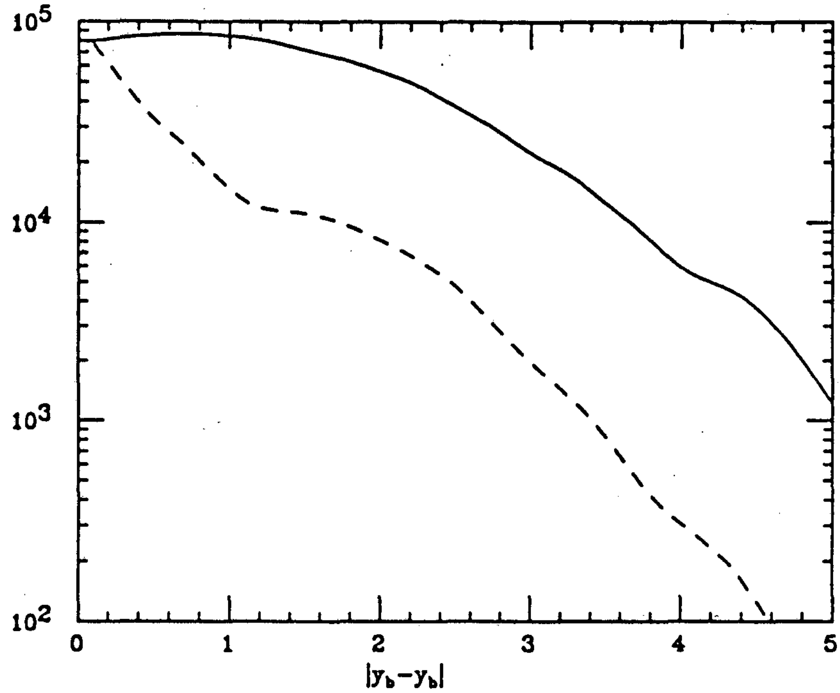

Figure 3. The distribution in the difference of rapidity $|y_b - y_{\bar{b}}|$ for the production of a $b\bar{b}$ pair at $\sqrt{s} = 40$ TeV. The solid line corresponds to the total $b\bar{b}$ rate while the dashed to that small part of the cross section where the b and $\bar{b}$ have transverse momenta greater that 100 GeV.

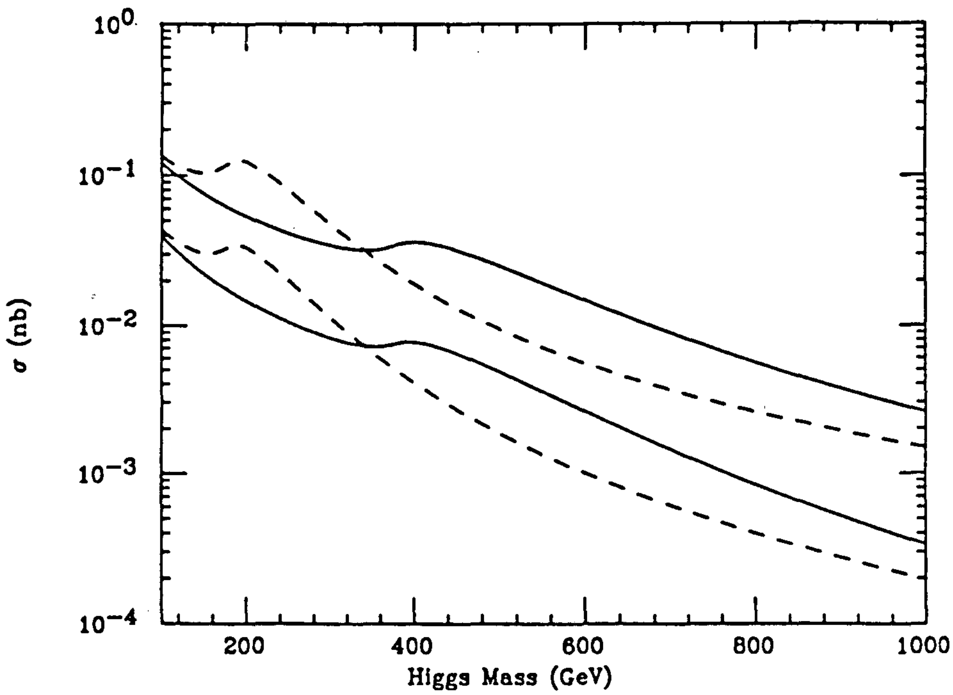

Figure 4. The total cross section for $pp \to H + X$ at $\sqrt{s}$ =17 TeV (lower lines) and 40 TeV (upper lines). The solid (dashed) lines correspond to top quark mass of 185 (85) GeV.

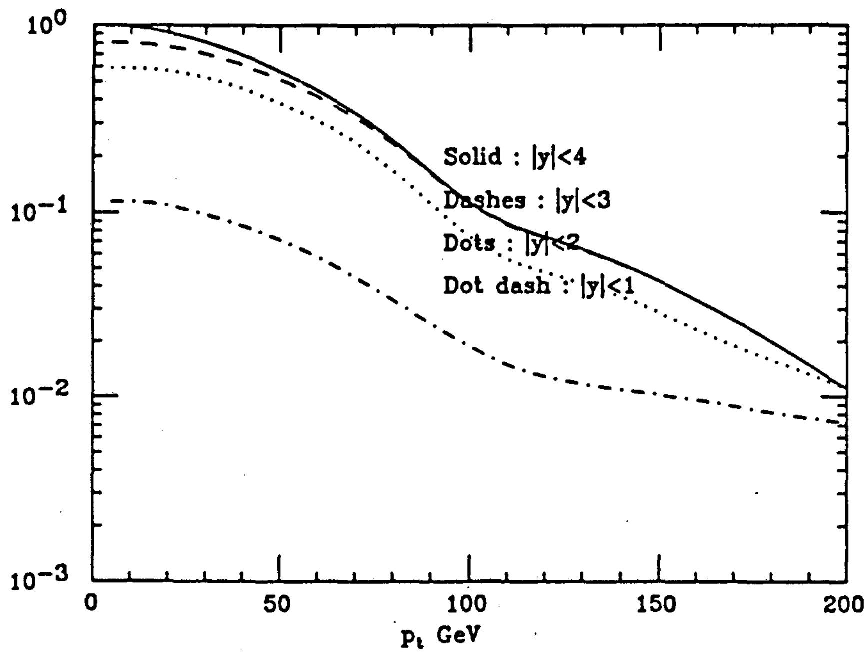

Figure 5. The acceptance for the 4 charged leptons from $H \to ZZ \to e^+e^-e^+e^-$. All leptons are required to have $|y| < y_0$ and $p_t > p_0$.

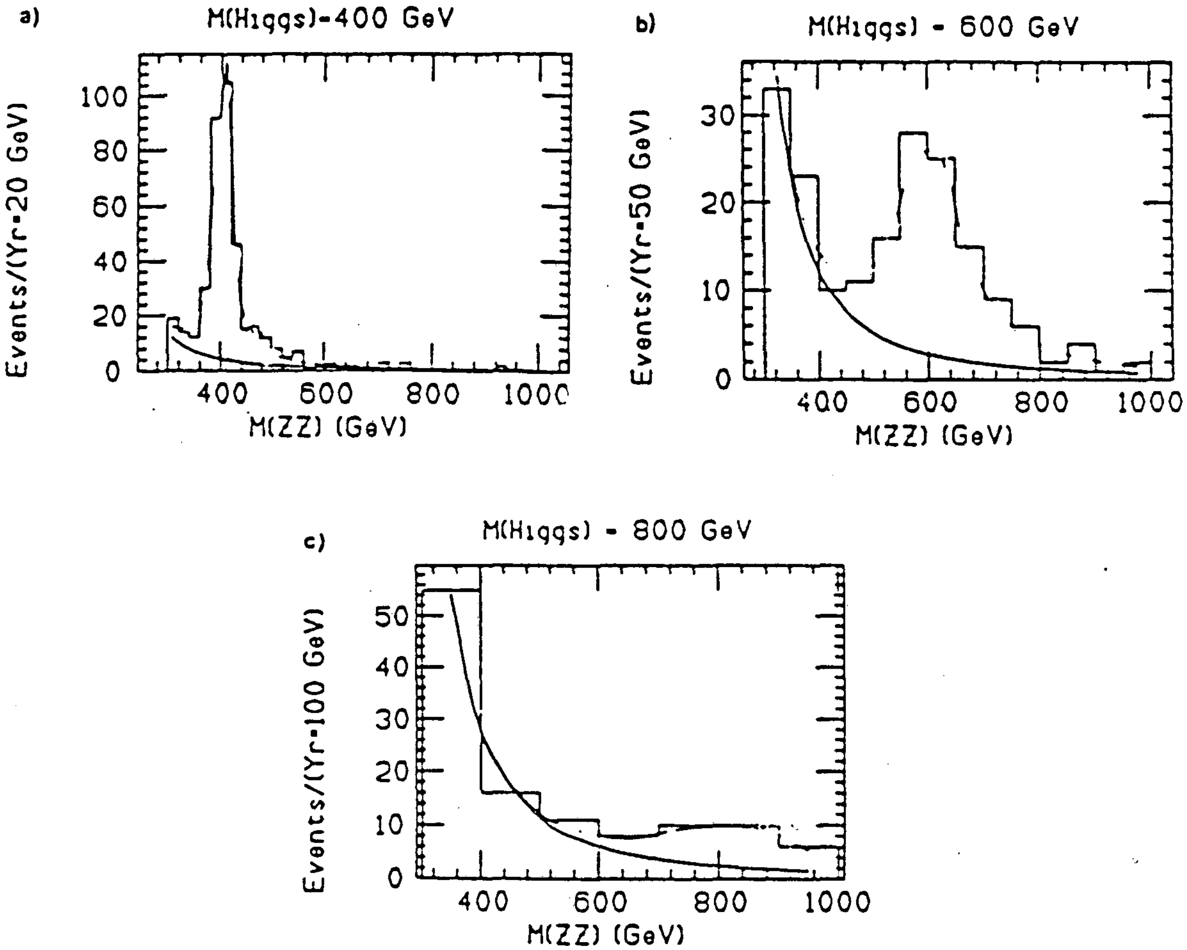

Figure 6. This distribution $d\sigma/dm$ for the production of a pair of Z bosons of invarient mass m at SSC for an integrated luminosity of $10^{40}cm^{-2}$. The peak is due to a Higgs boson of mass 400, 600, and 800 GeV. The smooth curve is the rate from the process $q\bar{q} \rightarrow ZZ$, while the histogram is the sum of this process and the Higgs production and decay. The quoted rates assume a top quark mass of 200 GeV and include the branching ratio for the Z's to decay either to e^+e^- or $\mu^+\mu^-$.[14]

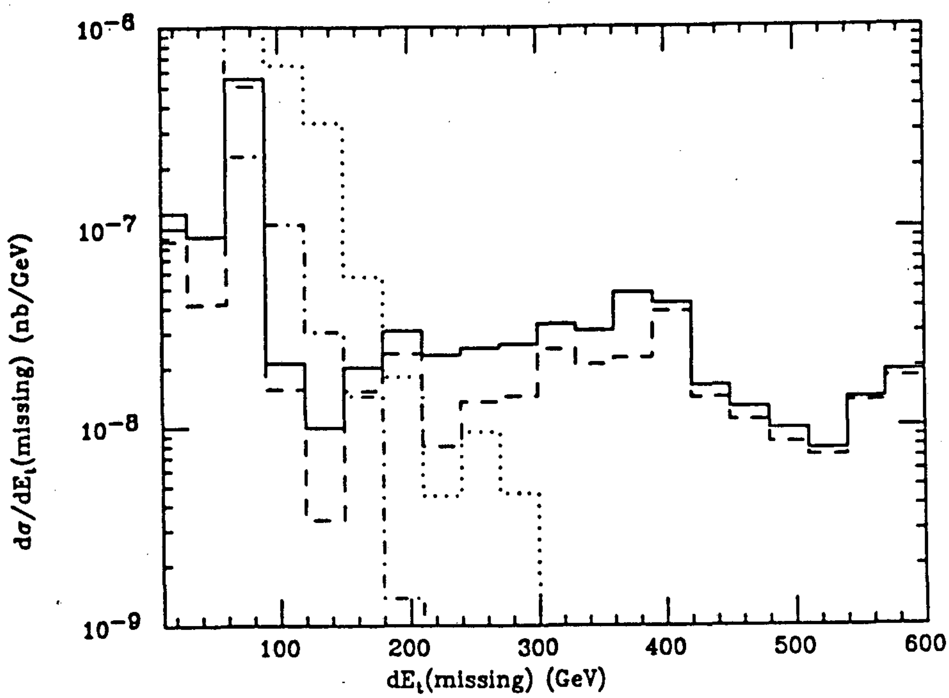

Figure 7. The distribution in missing transverse energy $d\sigma/dE_t(missing)$ arising from the process $pp \rightarrow H + X \rightarrow ZZ + X \rightarrow e^+e^-\nu\bar{\nu} + X$ for a Higgs mass of 700 GeV. The solid (dashed) histogram shows the distribution when the Z decaying to e^+e^- is required to have $p_t > 100$ (300) GeV. Also shown is the background from the process $pp \rightarrow Z + jets + X \rightarrow e^+e^- + jets + X$. Here the missing E_t arises from jets lost down the beam-hole. The detector is assumed to have perfect energy resolution at $|y| < 4.5$ and no detection of jets beyond this point. The dotted (dot-dashed) histogram corresponds to the Z having $p_t > 100$ (300) GeV.

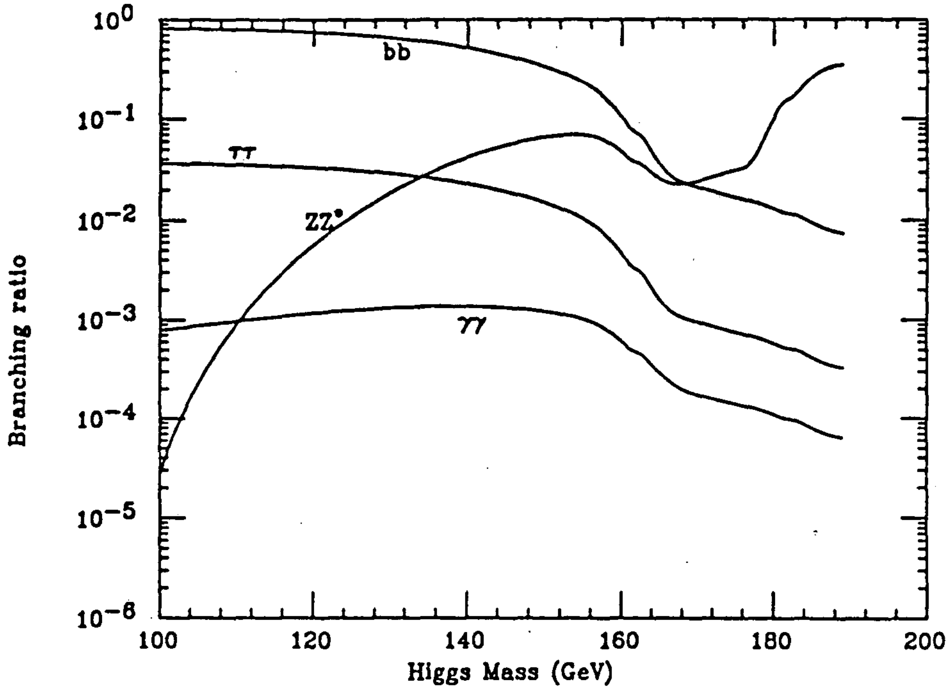

Figure 8. The branching ratios for Higgs decay as a function the Higgs mass assuming that the decay $H \to t\bar{t}$ is kinematically forbidden.

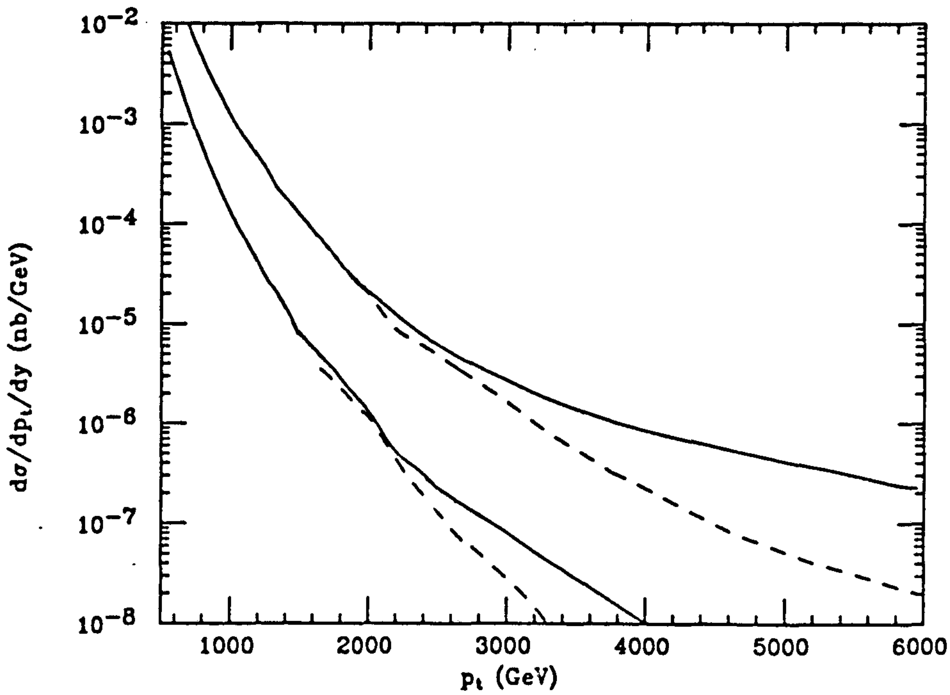

Figure 9. The cross section $d\sigma/dp_t/dy$ for the production of a jet in pp collisions at rapidity $y = 0$ as a function of the jet transverse momentum. The solid lines are the pure QCD prediction. The solid (dashed) show the cross section when a composite interaction between quarks is added with $\Lambda_{*}=$ 10 (20) TeV. The upper (lower) curves are for $\sqrt{s}$ = 40 (17) TeV.

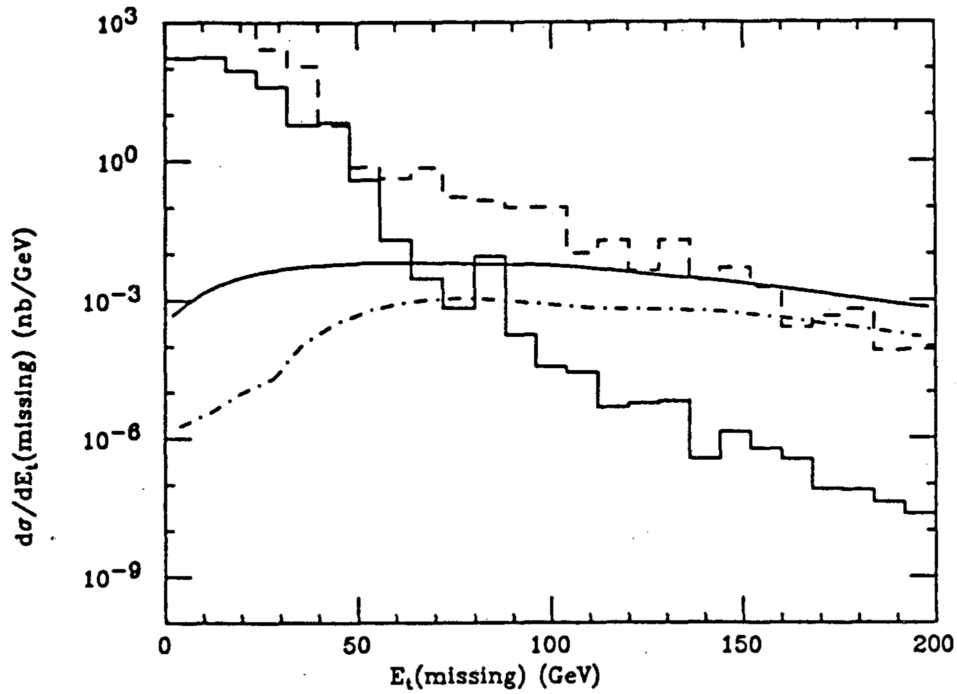

Figure 10. The missing transverse energy distributions resulting from gluino pair production for a gluino mass of 250 GeV at $\sqrt{s}$ = 40 TeV (solid curve), $Z(\rightarrow \nu\bar{\nu})$ plus 3 jets (dash-dotted curve), and 3 mismeasured jets (QCD) where resolution is as described in the text (solid histogram), and 4-jet (QCD) events in which one jet escapes though the beam hole *i.e.*has $|y| > 4.5$ (dashed histogram)

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