SSCL-Preprint-23

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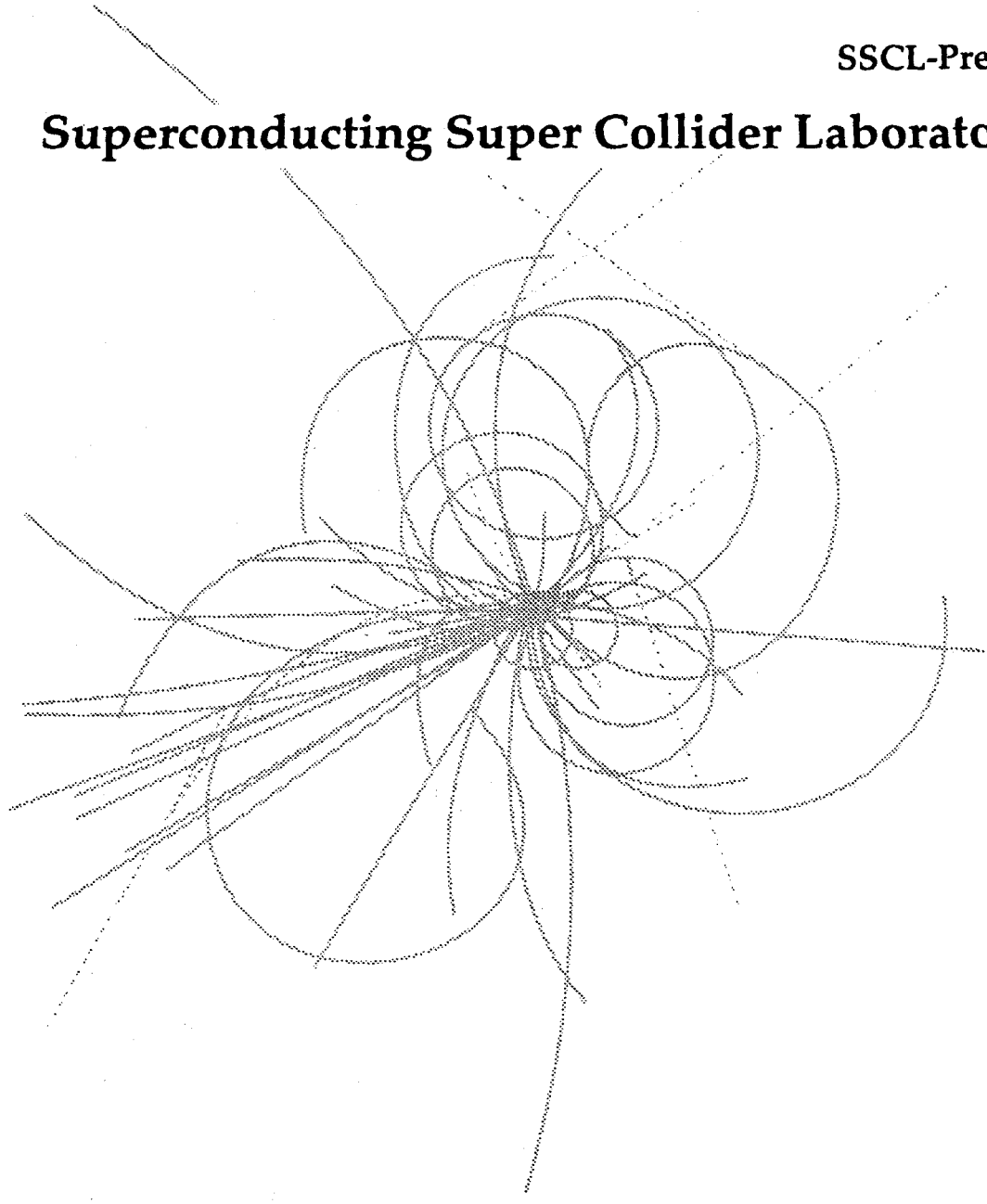
Superconducting Super Collider Laboratory



SSC Physics Signatures

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SSC PHYSICS SIGNATURES

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ABSTRACT

The main goals of the SSC physics program are to discover the origins of electroweak symmetry breaking and of quark and lepton masses, and more generally to search for any particles at the TeV mass scale. Signatures for this physics are reviewed.

1. Introduction

The main goals of SSC physics program are to discover the origin of electroweak symmetry breaking, to discover the origin of quark and lepton masses (which might or might not be the same), and to search for new particles at the TeV mass scale. These are the goals of the large detectors, the Solenoidal Detector Collaboration (SDC)[1,2] and Gammas-Electrons-Muons (GEM),[3,4] now being considered for approval. While only high-mass physics is discussed here, one should not forget that the SSC can do many other things. Expressions of Interest have been received to study B physics, using both the collider and external beams;[5,6,7] to study diffractive physics, both of the traditional low-p_T type and at moderately high p_T.[8,9] All of these are potentially interesting. One should also not forget that much of the high-mass physics discussed here might be done at the proposed Large Hadron Collider at CERN.

2. Physics Prospects

The standard model is in very good agreement with almost all existing data. For example, one can compare various determinations of $\sin^2\theta_W$:[10]

$$\begin{aligned}\sin^2\theta_W &= 0.2300 \pm 0.0030 \pm 0.0050 && (\nu_\mu N)\\ &= 0.2325 \pm 0.0010 \pm 0.0006 && (\nu_\mu e)\\ &= 0.2310 \pm 0.0070 && (\text{LEP})\end{aligned}$$

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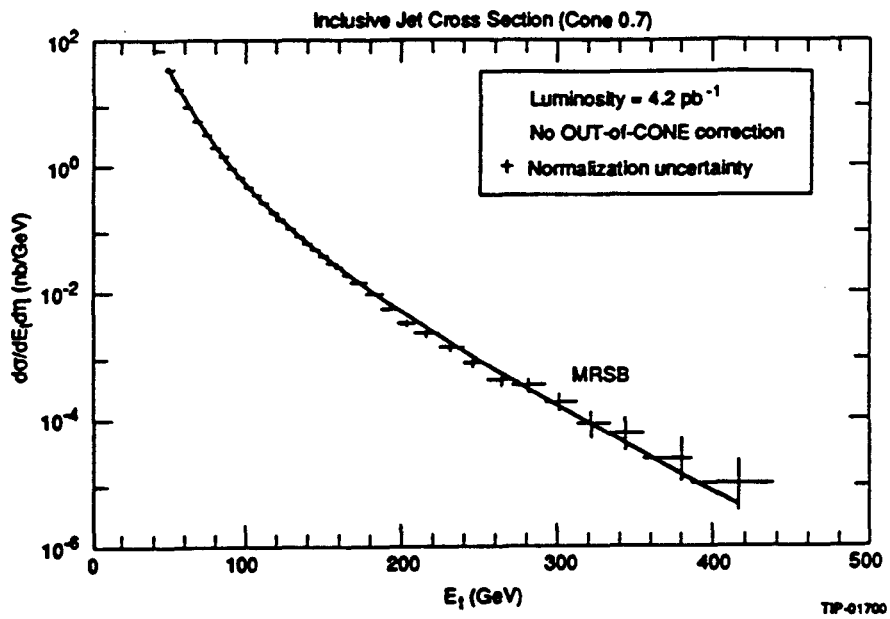

Figure 2.1: CDF jet cross section and perturbative QCD prediction.

The agreement of these values indicates that the standard model works well over the entire range of observed Q^2 values. QCD also agrees with all existing data, although it is less precise. A good example is provided by the jet cross section observed at the Tevatron,[11] Fig. 2.1, which agrees to better than a factor of two with the theoretical calculation over seven orders of magnitude.

The only missing particles of the standard model are the t quark and the Higgs boson. The t mass can be bounded by considering radiative corrections to the $W^{\pm}$ and Z^0 masses, while the H mass is bounded by direct searches at LEP:[12,13,14,15]

$$m_t = 130 \pm 40\,\text{GeV}$$
$$m_H > 48\,\text{GeV}$$

Lattice studies of the Higgs sector suggest an upper limit on the Higgs mass,[19]

$$m_H < 650\text{–}800\,\text{GeV}$$

if there is no new physics for $M \lesssim 1\,\text{TeV}$. This is a bit lower than but similar to bounds determined by unitarity constraints. Given these results, one expects any new physics to be at high mass and/or weakly coupled to ordinary matter.

It is possible to bound any new physics by its loop corrections to the W and Z propagators:[21]

$$\frac{\Pi_W\left(m_W^2\right) - \Pi_W(0)}{m_W^2} = \frac{\alpha\left(m_W^2\right)}{4\sin^2\theta_W\left(m_Z\right)} S_W$$

indicate. They also reflect the fact that any new particle must decay either into quanta of the standard model or into particles which are weakly coupled to ordinary matter and so produce missing energy. If a detector can detect all of these, it probably can also detect something quite unanticipated.

3. General Requirements

New particle must be either stable or decay into the quanta of the standard model — jets (quarks and gluons), leptons (e, μ, and τ), prompt photons, W and Z bosons — or decay into new particles which are undiscovered because they are weakly coupled to ordinary matter. Particles associated with electroweak symmetry breaking in particular tend to couple to heavy quarks, so tagging of b and other heavy quarks is useful. For the mass scales not observable at LEP or the Tevatron and so of interest at the SSC, the typical kinematic values of interest are:

$$\begin{aligned} p_T &\gtrsim 15\,\mathrm{GeV},\ |\eta| \lesssim 3 && \text{for leptons} \\ p_T &\gtrsim 25\,\mathrm{GeV},\ |\eta| \lesssim 3 && \text{for jets} \\ p_T &\gtrsim 50\,\mathrm{GeV},\ |\eta| \lesssim 5.5 && \text{for } p_{T,\,\mathrm{miss}} \end{aligned}$$

New particles are typically produced with $p_T \lesssim m$ and decay into several different quanta. Hence it is important to detect all the quanta of the standard model over a large $\Delta\Omega$, leading to large detectors. Within this general framework there are two different and complementary approaches. One approach, exemplified by SDC, emphasizes tracking, giving more detailed information about the events and redundancy between tracking and calorimetry. The other approach, exemplified by L*, E/T, and GEM, emphasizes calorimetry, allowing better calorimetry and better performance at high luminosity because of less dependence on central tracking.

4. Top

The top quark is the one new particle which must exist, since it is by definition the partner of the b, which is known to be in a weak isospin doublet. Direct searches for the t in $p\bar{p}$ collisions have established a lower bound[15]

$$m_t > 89\,\mathrm{GeV},$$

assuming standard model production[16] and decays. Otherwise the only bound is from LEP and is about $m_Z/2$. The mass inferred from radiative corrections, $m_t = 130 \pm 40$ GeV, will probably allow discovery at the Tevatron if the proposed upgrades are made. If not, then the top can be trivially discovered at the SSC by the process

$$gg \to t\bar{t} \to e^{\pm}\mu^{\mp}X,$$

even if the t mass is much larger than expected.

$$\frac{\Pi_Z(m_Z^2) - \Pi_Z(0)}{m_Z^2} = \frac{\alpha(m_Z^2)}{\sin^2 2\theta_W} S_Z$$
$$\frac{\Pi_W(0)}{m_W^2} - \frac{\Pi_Z(0)}{m_Z^2} = \alpha(m_Z^2)\, T$$

with $S = S_W \approx S_Z$.[21] Present data give[22]

$$T = -0.06 \pm 0.23$$
$$S = -2.2 \pm 1.3$$

This is already sufficient to constrain, for example, some technicolor models, and the bounds will improve with future experiments.

The main problem of the standard model is with the Higgs mechanism used to produce electroweak symmetry breaking and fermion masses. It is responsible for most of the 19 arbitrary parameters in the model. It is also responsible for the naturalness problem: radiative corrections give contributions to the Higgs mass of order the heaviest mass in the theory, e.g., the Planck mass. Despite these problems, the Higgs mechanism does determine the mass scale for electroweak symmetry breaking,

$$v = 246\,\mathrm{GeV}.$$

Any new physics related to electroweak symmetry breaking must occur at $M \sim v$, or more generally at $M \lesssim 1\,\mathrm{TeV}$.

There have been only a few general ideas for explaining electroweak symmetry breaking:

- The standard model Higgs boson;
- Multiple elementary Higgs bosons, which complicate the standard model but do not solve any of its problems;
- A $t\bar{t}$ bound state effective Higgs, which is possible only because the top is heavy;
- Technicolor models, which replace the Higgs with bound states of new heavy fermions;
- Supersymmetry, which provides a natural framework for elementary scalars;
- Composite fermions which somehow generate dynamical masses.

In addition to particles directly related to electroweak symmetry breaking, the SSC can also look for other possible new particles, including new quarks, possible including the t quark, and new W' and Z' bosons. Almost all of these ideas have been discussed at least since 1984,[23] although the models have been greatly elaborated since then.

Lists of possible new physics like this form the basis for the "physics benchmarks" used to test SSC detectors.[24] Almost all of these possibilities could be discovered by the detectors proposed for the SSC. But while these benchmarks represent plausible discoveries, they are much more useful as guides to the design of detectors than the intrinsic plausibility of the underlying models might

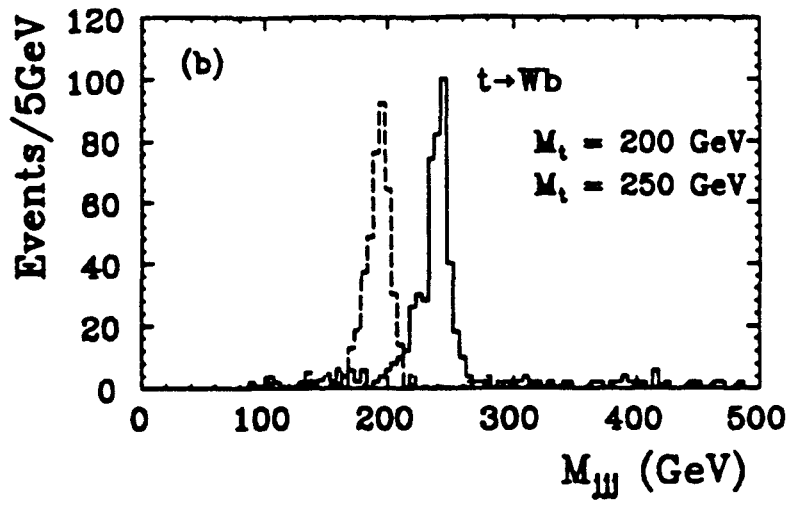

Figure 4.1: $t \to Wb$ jet mass distribution using a $b \to \mu^-\mu^+X$ tag. (L*)

4.1. Mass

Even if the top is discovered at the Tevatron, detailed measurements will need the SSC. The top mass is clearly a basic phenomenological parameter, especially since the fact that the t is so heavy suggests that it may play unique dynamical role. The simplest way to measure m_t is to measure the top production cross section. Since

$$\sigma \approx 10\,\mathrm{nb} \quad \text{for} \quad m_t = 140\,\mathrm{GeV},$$

the statistical error will be negligible. The theoretical uncertainty from the gluon distribution, higher order QCD corrections, and trigger acceptance is probably about 50%, giving a determination of m_t to about 10%, assuming the standard model for its production and decay.

A direct measurement of the mass can be made by reconstructing the $W \to q\bar{q}'$ and Wb masses with a single lepton trigger:

$$t + \bar{t} \to \ell^+\nu b + q\bar{q}'\bar{b}$$

This is an example of jet spectroscopy. To reduce the combinatorial background, SDC[2] proposes to tag b jets with their vertex detector. L* requires two non-isolated muons to tag the b jet, giving a clean sample, albeit with low efficiency. The resulting simulated W and top masses are shown in Fig. 4.1. Based on the difference between the input and reconstructed masses, the error on the m_t is a few GeV.[17] The W mass provides a check on the accuracy of jet measurements.

In addition to these methods, GEM[4] suggests selecting events containing a lepton and a jet with $|\vec{p}_{T,\ell} + \vec{p}_{T,\mathrm{jet}}| > 300\,\mathrm{GeV}$. Then the highest p_T recoil jet

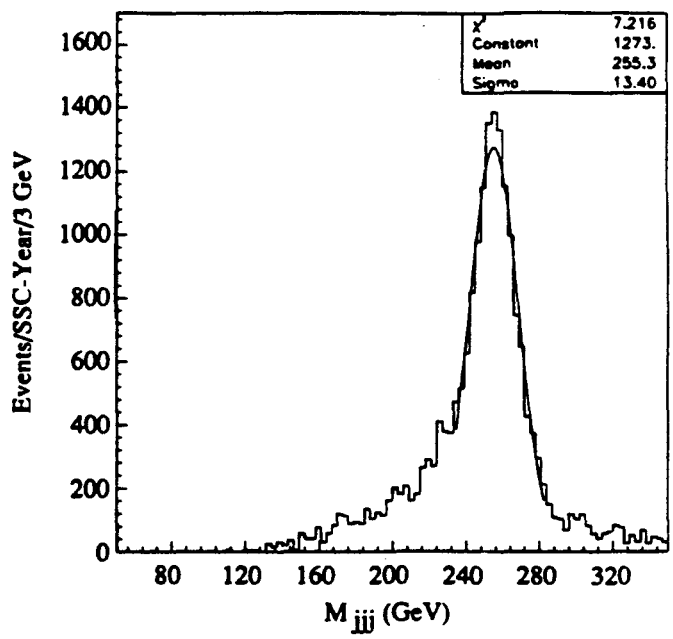

Figure 4.2: $t \to Wb$ jet mass using a large $p_{T,t}$ selection. (GEM)

with two other jets in a cone $\Delta R = 1.0$ is selected, with little additional energy in a larger cone $\Delta R = 1.3$, and the three-jet mass is reconstructed. The result, Fig. 4.2, shows a background which is smaller than that found by SDC and comparable to that found by L* with a double muon tag.

Finally, it is possible to use the high statistics available at the SSC to find mean of a kinematic distribution, e.g.

$$\begin{aligned} M(\ell_1\ell_2): &\quad t + \bar{t} \to \ell_1\nu b + \ell_2\nu\bar{b} \\ M(\ell_1 b): &\quad t \to \ell_1\nu b \\ M(\ell_1\ell_3): &\quad t \to \ell_1\nu b,\ b \to \ell_3 X. \end{aligned}$$

These distributions may be easier to measure precisely, although the connection to m_t is more indirect.

The high statistics available at the SSC allow many possible analyses, allowing checks of systematics and possibly providing the first hint of something nonstandard about top physics.

4.2. Decays

Top decays are not very interesting in standard model. It is important to verify that $t \to Wb$ is dominant to be certain that a new quark is in fact the top. This can be done using b-tagging with a vertex detector and/or with nonisolated muons. It is possible that a b' could be lighter than the t, so one needs to do

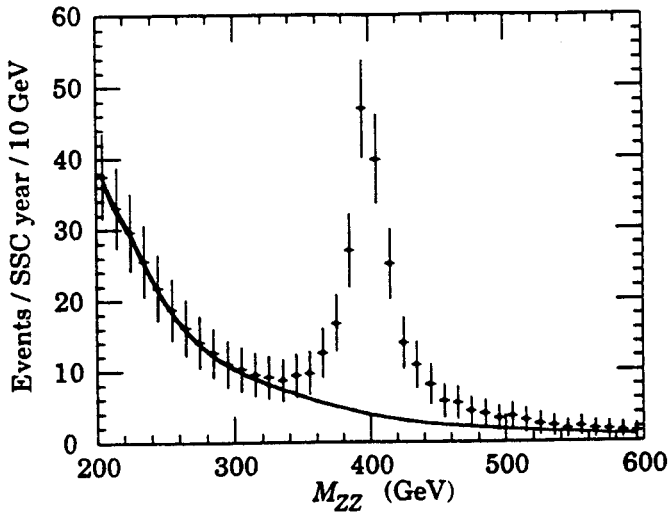

Figure 5.1: $H \to Z^0 Z^0 \to \ell^+\ell^-\ell^+\ell^-$ signal and $Z^0 Z^0$ continuum background for $m_H = 400\,\mathrm{GeV}$. (SDC)

the tagging well enough to distinguish $b' \to Wc$ from $t \to Wb$. It would be nice also to measure the Cabibbo suppressed decay $t \to Ws$, but there seems to be no good way to identify s quark jets sufficiently well.

Nonstandard decays of the t are of course possible. If there exists a charged Higgs boson H^+ lighter than t, then a substantial branching ratio for $t \to H^+ b$ is expected, with $H^+ \to c\bar{s}$ or $H^+ \to \tau^+\nu$.[26] In either case one can trigger on one t or $\bar{t}$ decaying through Wb to a lepton. For $H^+ \to c\bar{s}$, one would reconstruct the jet masses as for the $t \to Wb \to jjj$ decay, imposing in addition a veto $M_{jj} \neq M_W$. This gives a few percent meausrement of the H^+ mass provided that the combined brancing ratio is greater than about 1%. If $H^+ \to \tau^+\nu$ dominates, one must test $e/\mu/\tau$ universality by measuring the ratio of one-prong jets to leptons. The τ misidentification seems small even without detecting the τ vertex, and the sensitivity for the combined branching ratio is also of order 1%.

Other plausible nonstandard decays include $t \to Z^0 c$, which could be large if there were a fourth generation of quarks strongly mixed with the t, and the supersymmetric mode $t \to \tilde{t}\tilde{\chi}_1^0$. These modes do not seem to put any particular constraints on the detectors.

5. Higgs

The Higgs boson is the most unsatisfactory part of the standard model. It is responsible for most of the 19 arbitrary parameters in the theory. Furthermore, a low Higgs mass is unnatural[18] in the presence of high mass scales, and at least one such scale, the Planck mass, must be present in any theory which

incorporates gravity. Nevertheless, being able to detect the standard Higgs boson is an important benchmark for any SSC detector both for its own sake and for what it indicates about the ability to study WW physics. The masses of interest range from about 80 GeV, the upper limit which would be observable at LEP-200, to a theoretical upper limit $m_H \geq 650$–800 GeV determined by lattice studies of the gauge-Higgs theory.[19] This is a refinement of the old limit from perturbative unitarity.[20]

Since the top is heavy, it is possible[27] to replace the Higgs boson with a $t\bar{t}$ bound state made by some unknown new dynamics at a scale $\Lambda \sim 10^{15}$ GeV. At this new scale, $m_H = 2m_t$, but the renormalizaton group then implies $m_H \approx m_t$. This picture gives essentially the standard model up to masses of order Λ with a relatively light Higgs boson.

The search for the Higgs boson naturally divides into the heavy mass region, $m_H > 2m_Z$, where the dominant decays $H \to W^+W^-$ and $H \to Z^0Z^0$ can be used, and the intermediate mass region, $80\,\text{GeV} < m_H < 2m_Z$, where backgrounds overwhelm the dominant $H \to b\bar{b}$ and rare decays such as $H \to \gamma\gamma$ and $H \to ZZ^*$ must be used.[28]

5.1. Heavy Higgs

For $m_H > 2m_Z$, $\Gamma_H(W^+W^-) \approx 2\gamma_H(Z^0Z^0)$. Since the W^+W^- mode has a large background from $t\bar{t}$ events and is harder to reconstruct, it is natural to concentrate on the Z^0Z^0 mode.

$H \to Z^0Z^0 \to \ell^+\ell^-\ell^+\ell^-$, where $\ell = e, \mu$, has been beaten to death.[29] If the $Z^0 \to \ell^+\ell^-$ mass resolution is comparable to the Z^0 width, then only known background is the Z^0Z^0 continuum. The only problem with this mode is that the statistics become small for $m_H \gtrsim 600$ GeV; see Fig. 5.1. For higher masses one must either rely on $\mathcal{L} \sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ or use Z^0 decay modes with larger branching ratios but more backgrounds.

$H \to Z^0Z^0 \to \ell^+\ell^-\tau^+\tau^-$ has a rate equal to the 4ℓ rate. If the τ mass is ignored, then one has a 1-constraint fit, using the two components of $\vec{p}_{T,\text{miss}}$ plus the Z^0 mass to determine two sums of missing neutrino energies. The backgrounds are probably small, especially if one uses a vertex detector or requires at least one of the τ's to decay leptonically. Unfortunately, no thorough background study has been done, although the backgrounds seem to be small.[31]

$H \to Z^0Z^0 \to \ell^+\ell^-\nu\bar{\nu}$ gives six times the 4ℓ rate.[30] There is a large background from Z^0 + jets, where the jets are somehow missed. This can be rejected with a perfect detector covering $|\eta| \lesssim 5.5$.[32] A realistic estimate of the background requires a full detector simulation. The simulations which have been done are not complete, but they have used full GEANT simulations to examine the effect of the calorimeter edges at $\eta \approx 3$ and the transverse shower spreading in the forward calorimeter.[33] It seems that these are not fatal and that sufficient background rejection can be obtained with coverage of $\eta \lesssim 5$.

$H \to Z^0Z^0 \to \ell^+\ell^-q\bar{q}$ has a large branching ratio but also a large background from Z^0 + jets. Several studies of the analogous $H \to W^+W^-$ mode with one hadronic decay were made assuming light t quarks but were inclusive.

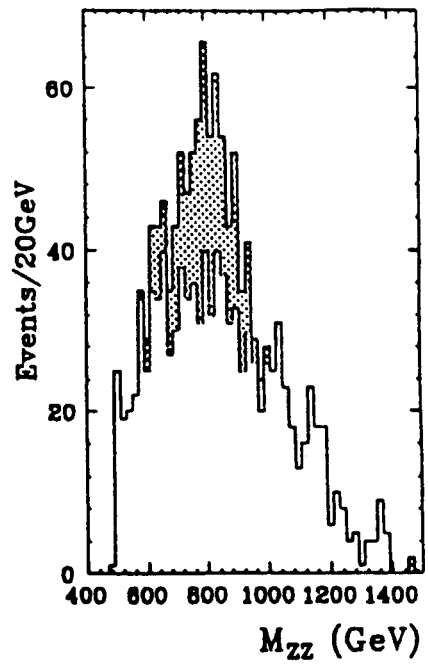

Figure 5.2: $H \to Z^0 Z^0 \to \ell^+\ell^- q\bar{q}$ mass distribution from 800 GeV Higgs and background. (L*)

Given the large additional background from $t\bar{t}$, this channel looks difficult. The first successful analysis of the $Z^0 Z^0$ mode with one hadronic decay was made by L*,[25] using the following cuts for $m_H = 800$ GeV:

$p_{T,Z} > 240$ GeV

2 jets in $\Delta\phi = \pm 50°$ from Z^0.

This gave 210 events on a background of 640, which is statistically significant, although the signal and background peak in the same place; see Fig. 5.2.

For an 800 GeV Higgs, about half the cross section comes from WW fusion. Since the W bosons are radiated from valence quarks, these events generally have jets with $p_T \sim m_W$ at large η. An EMPACT/TEXAS analysis[31] and later a GEM analysis[4] found an improvement in the signal/background by requiring jet with $p_T > 50$ GeV and $\eta > 3$; the latest GEM analysis is shown in Fig. 5.3. Even if forward jet tagging is not essential for observing the signal, it is an important confirmation of the production dynamics.

One might also use cuts or the shape of the recoil jets and cuts on the multiplicity of the associated event.[34] The usefulness of these, especially of the multiplicity cut, depend on a detailed understanding of the event structure.

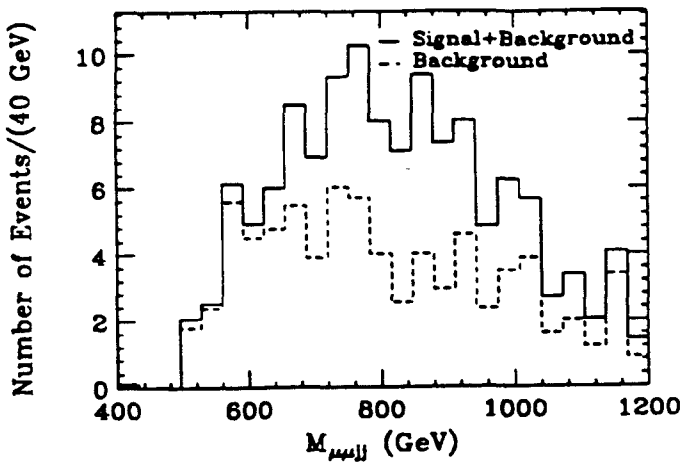

Figure 5.3: $H \to Z^0 Z^0 \to \ell^+\ell^- q\bar{q}$ mass distribution from 800 GeV Higgs and background with forward jet tagging. (GEM)

5.2. Intermediate Mass Higgs

For $m_H < 2m_Z$ the dominant decays are $H \to b\bar{b}$ and $H \to \tau^+\tau^-$. Both suffer from large backgrounds, and the $\tau^+\tau^-$ decay cannot be reconstructed except for $m_{T,H} \gtrsim m_H$. Hence one is forced[26] to rely on the rare decays $H \to \gamma\gamma$ and $H \to ZZ^*$.

$H \to \gamma\gamma$ has a branching ratio of order 10^{-3}. The irreducible background comes from the QCD processes $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$. Since the Higgs is narrow in this mass range, this irreducible background can be rejected if $\Delta M_{\gamma\gamma}/M_{\gamma\gamma} \lesssim 1\%$. This requires a high resolution electromagnetic calorimeter and determination of the event vertex, either by directional information from the calorimeter or by finding the z-vertex using charged particle tracks. If multiple interactions occur in the same bunch crossing, the most probable vertex can be determined by selecting the one with the highest multiplicity of tracks.[25]

There is also a large potential background from QCD jets which fragment into hard leading π^0's and so give electromagnetic energy. The required γ/jet rejection is about 10^{-4}. It appears possible to achieve this using a combination of calorimetric and tracking isolation cuts and perhaps information from a preshower detector in front of the calorimeter.[4] A large part of the rejection must be achieved at the trigger level to make the trigger manageable.

The $H \to \gamma\gamma$ signal/background might be improved by looking for associated Higgs production. Kleiss and Stirling[35] proposed to look for $q\bar{q}' \to WH$ production. The real background in this channel is small, but only about 6 events/yr are produced. An alternative is to look for $gg \to Ht\bar{t} \to \gamma\gamma\ell\nu X$, giving about 50 events/yr.[36] The backgrounds from $t\bar{t}\gamma\gamma$ have been calculated and are manageable but not negligible.[37] There are also potential backgrounds from jets

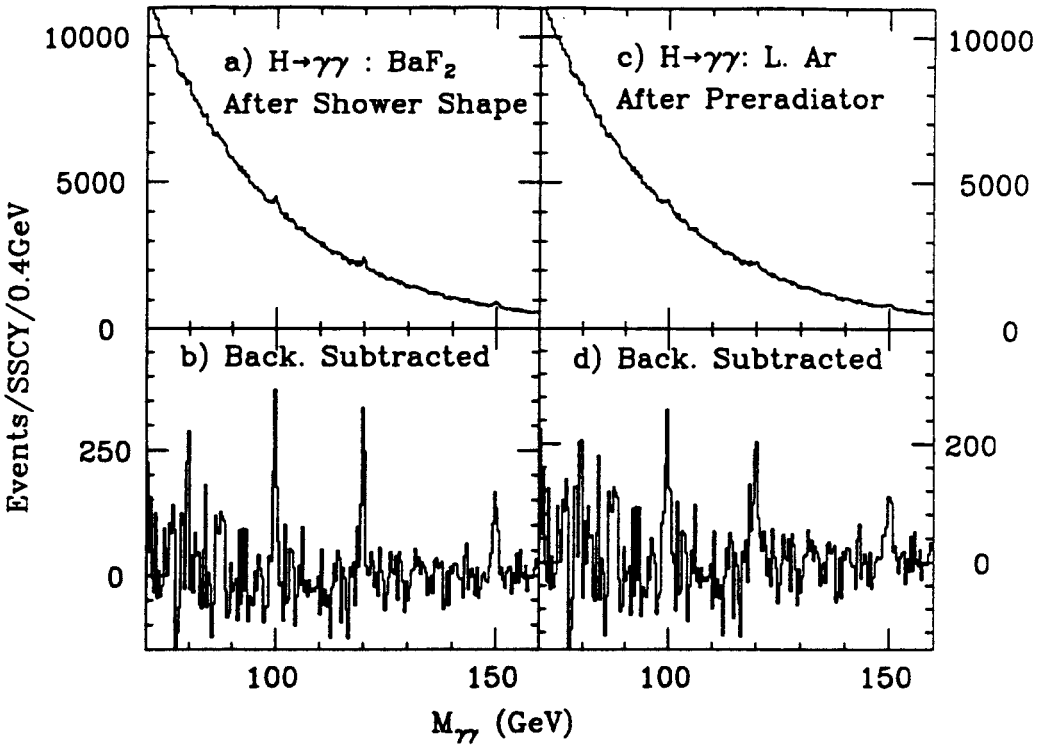

Figure 5.4: $H \to \gamma\gamma$ and backgrounds from real $\gamma\gamma$ events and from jets for two different calorimeters. (GEM)

giving π^0's which are also not negligible. Whatever the true background situation, it is clear that such tagged processes will at best give a small number of events.

For $140\,\mathrm{GeV} \lesssim m_H < 2m_Z$, the rare decay $H \to Z^0 Z^{0*} \to \ell^+\ell^-\ell^+\ell^-$ has an observable branching ratio. Backgrounds come from $Z^0\gamma^*$, $Z^0 b\bar{b}$ and $Z^0 t\bar{t}$ production. Since the Higgs is narrow in this mass range, the backgrounds can be minimized by good mass resolution. The estimated signal and background[2] are shown in Fig. 5.5. To detect this signal, it is essential to have an efficient $Z \to \ell^+\ell^-$ trigger and to detect low-p_T leptons.

For $2m_W < m_H < 2m_Z$, the $H \to ZZ^*$ branching ratio becomes small because of $H \to W^+W^-$ decays. In this mass range it may be possible to confirm a $H \to ZZ^*$ signal by detecting $H \to W^+W^- \to e^\pm\mu^\mp X$. The signal for $M_{\ell\ell} \sim m_H/2$ is about equal to the background from continuum W^+W^- pair production. To veto the very large background from $t\bar{t}$ production, it is essential to detect extra jets very efficiently. It is unclear whether this is possible; a realistic study is needed.

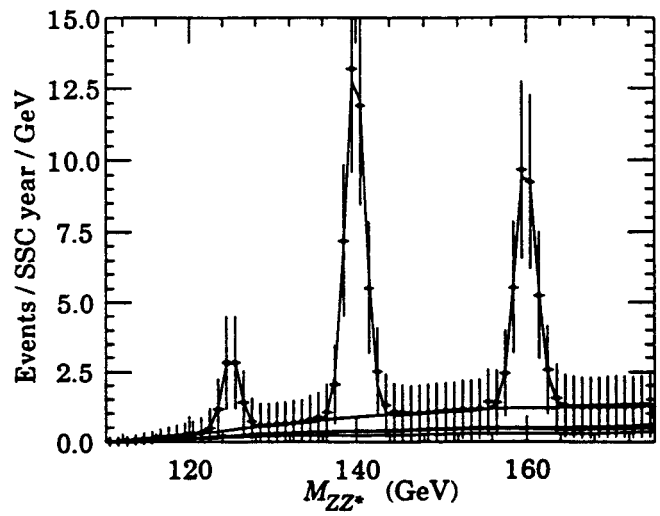

Figure 5.5: $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ signal and cumulative backgrounds. (SDC)

5.3. Nonstandard Higgs

Nonstandard Higgs bosons are not very unlikely: supersymmetry provides the only known natural framework for elementary scalars, and it requires at least two Higgs doublets and hence both charged and several neutral Higgs bosons.[38]

A possible signature for charged Higgs $H^\pm$ is $gb \to H^-t$, $H^- \to W^-h^0$. A similar possible signature for the $CP = -1$ neutral Higgs A is $gg \to A^0$, $A^0 \to Z^0h^0$. In both cases, the light h^0 mass is presumably known, but b jet tagging is probably necessary to reject the background. More work on signatures of this sort should be done.

6. Technicolor

In technicolor models,[39] elementary Higgs bosons are replaced by bound states of technifermions made by new technicolor interactions which become strong at the 1 TeV scale. Such models explain the $W^\pm$ and Z^0 masses, but they do not generate fermion masses unless extended technicolor interactions are introduced. These potentially give flavor-changing neutral currents much larger than the experimental bounds. In "walking" technicolor models,[40] the couplings run slowly between the technicolor and extended technicolor scales, resulting in much smaller flavor-changing neutral currents.

The minimal technicolor model gives only a QCD-like spectrum at the 1 TeV mass scale, with the longitudinal $W^\pm$ and Z^0 playing the role of pions. This is difficult to detect even at the SSC. One must look for, e.g., $\rho_{TC}^\pm \to W^\pm Z^0$, which is produced by WW fusion and by $W - \rho_{TC}$ mixing. The experimental cross section with leptonic $W^\pm$ and Z^0 decays is tiny,[41] as shown in Fig. 6.1.

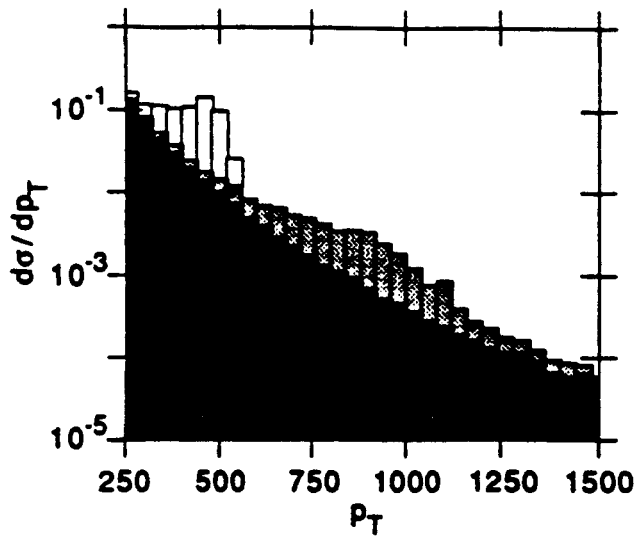

Figure 6.1: p_T, Z distribution for $\rho_{TC}^{\pm} \to W^{\pm}Z^0$ and standard model backgrounds with leptonic decays. Ref. 41

One might also look for mixed leptonic-hadronic decays like those considered for the standard model Higgs, but no careful study has been done.

In the minimal model one can also look for $\omega_{TC} \to Z^0\gamma$.[2] This gives a better signature, but the rates are still tiny,[2] as shown in Fig. 6.2. This process does illustrate the importance of identifying isolated single photons.

Fortunately, realistic technicolor models[42] have much more structure and are easier to detect. Typical ingredients of such models include:

- More technifermions, some with $SU(3)$ color.
- "Walking" couplings above Λ_{TC}. May change masses and decays.
- Perhaps multiple mass scales.
- Pseudo-Goldstone bosons.

The Pseudo-Goldstone bosons in particular give promising signatures. For example, a color-3 leptoquark P_3 is produced with a cross section about 15% that of a quark of the same mass. It probably decays dominantly into τb, which can be reconstructed in principle using $\vec{p}_{T,\,\mathrm{miss}}$ to determine two sums of missing neutrino energies. It may also be possible to look for one $P_3 \to \mu b$ decay, since it is likely that

$$\frac{\Gamma(\mu b)}{\Gamma(\tau b)} \sim \left(\frac{m_\mu}{m_\tau}\right)^2 \sin^2\theta.$$

This would give a much better signature. A good background study is needed.

Another possible technicolor signature is $P_8 \to t\bar{t}$. This was studied[43] for $m_t = 20\,\mathrm{GeV}$ but has not been reconsidered since it was learned that the top is heavy. Again, a realistic study is needed.

Finally, technicolor models might also give narrow colored resonances ρ_{TC}^8 decaying into leptoquarks or jets.[44] Such signatures are model dependent but

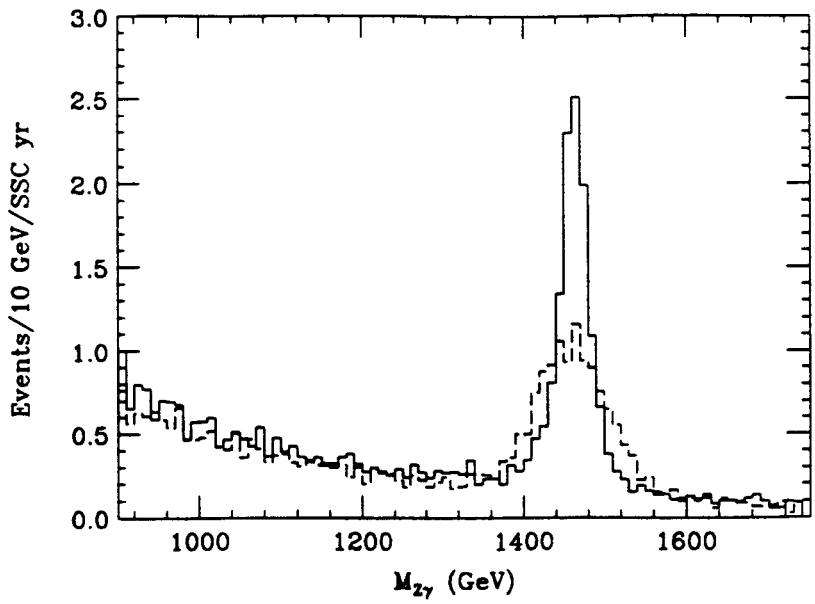

Figure 6.2: $\omega_{TC} \to Z^0\gamma$ cross section and standard model backgrounds.

indicate the importance of having detectors able to look at the full range of possible signatures.

7. Supersymmetry

Supersymmetry at the 1 TeV scale would solve the naturalness problem of the standard model. In addition, supersymmetry provides a plausible example of a model with with complex signatures and with calculable production and decay rates.

The minimal supersymmetric extension of the standard model[38] has a conserved R parity, with $R = 1$ for all ordinary particles and $R = -1$ for their supersymmetric partners. It requires two Higgs doublets, implying three neutral and a pair of charged Higgs bosons plus supersymmetric partners for all the ordinary particles. The color singlet superparticles are:

$$\tilde{\gamma},\ \tilde{Z},\ \tilde{h}^0,\ \tilde{H}^0 \Rightarrow \tilde{\chi}_i^0$$
$$\tilde{W}^\pm,\ \tilde{H}^\pm \Rightarrow \tilde{\chi}_i^\pm$$

R-parity requires that supersymmetric particles be produced in pairs and decay to the lightest supersymmetric particle χ_1^0, which is weakly interacting and so escapes, producing missing energy. Heavier $\tilde{\chi}$'s decay to lighter ones, giving complex cascade decays.[45]

There are significant limits on the minimal supersymmetric model from LEP, although these are complicated by t-quark loop corrections.[46] The present values of the $W^{\pm}$ and Z^0 masses are inconsistent with the assumption of grand unification of the couplings but can be made consistent[47] by introducing supersymmetric particles with $m \sim 1\,\mathrm{TeV}$. Unfortunately, the results of this analysis are extremely sensitive to detailed assumptions about the standard model and the boundary conditions at the unification scale, so the conclusions about supersymmetry are inclusive even if one accepts the assumption of grand unification.

Recent analyses have concentrated on gluinos, since their decays are most affected by the cascade decays characteristic of the minimal supersymmetric model. A "typical" 750 GeV gluino event is

$$g + g \to \tilde{g} + \tilde{g}$$

$$\begin{array}{ll} \tilde{g}_1 \to \tilde{\chi}_4^0 q\bar{q} & \tilde{g}_2 \to \tilde{\chi}_2^+ q\bar{q}' \\ \tilde{\chi}_4^0 \to \tilde{\chi}_1^+ W^- & \tilde{\chi}_2^+ \to \tilde{\chi}_2^0 W^+ \\ \tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu & \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h^0 \end{array}$$

This event, for which all the branching ratios are not small, contains seven undiscovered particles. Obviously, such a rich theory gives many possible experimental signatures.

7.1. Missing p_T

Since the lightest supersymmetric particle $\tilde{\chi}_1^0$ is weakly interacting and escapes any detector, the basic signature for supersymmetry is missing energy. The physics backgrounds are neutrinos from c, b, t quarks and from $W^{\pm}$ and Z^0 produced at large p_T by QCD processes. These backgrounds are less than the signal[48,4] after cuts designed to select heavy particle production with $p_T \lesssim m$; see Fig. 7.1. Detector effects such as the transition between the endcap and forward calorimeters at $\eta \approx 3$ and the resolution $\Delta p_T/p_T \lesssim 10\%$ in the forward calorimeter do not overwhelm the signature. Therefore, while the $\not{E}_T$ signature clearly depends on the global performance of the detector, it appears to be possible to detect.

7.2. Like-sign Dileptons

Since the gluino is a Majorana fermion, it decays equally into $\ell^+ X$ and $\ell^- \bar{X}$, giving substantial rates for like-sign dileptons. The backgrounds for isolated like-sign dileptons come from $t\bar{t}$ events in which a b quark happens to give an isolated lepton, from $W^{\pm}W^{\pm}$ events, and from various other small cross sections. All of these have been shown to be small compared to the gluino signal.[49] Hence the like-sign dilepton signature can be used to identify the Majorana fermion gluino characteristic of the minimal supersymmetric model. To detect this signal, it is useful to measure the signs of electrons as well as muons.

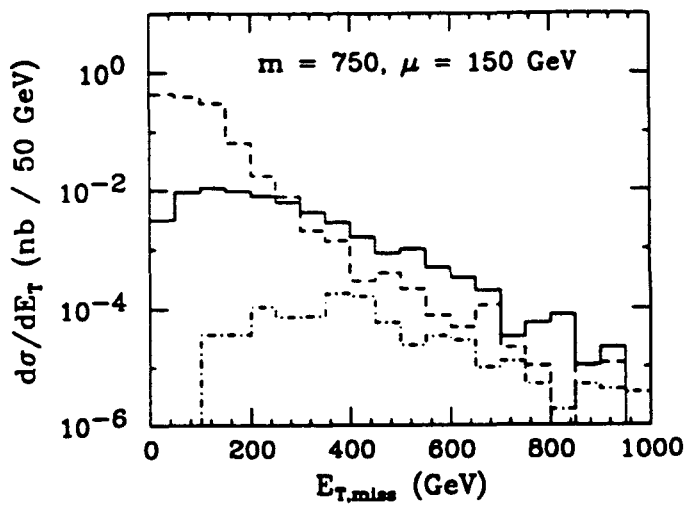

Figure 7.1: SUSY signatures and backgrounds. Solid: gluino, $m = 750\,\mathrm{GeV}$. Dashed: Heavy quark background. Dotted: $Z \to \nu\bar{\nu}$ background. (EMPACT/TEXAS)

The minimal supersymmetric model also predicts a variety of multilepton signatures and $Z^0 \to \ell^+\ell^-$ plus lepton signatures, all associated with missing transverse energy.[49]

It therefore appears that supersymmetry at the 1 TeV mass scale can be detected at the SSC. The open questions relate mainly to the question of determining all the parameters of the supersymmetric model, including the masses of the χ_i states appearing in gluino decays. To do this, it it minimally necessary to reconstruct all the standard model states appearing in the cascade decays, including in particular $W \to q\bar{q}'$. This seems to be possible but requires good lepton identification and hadron resolution in complex events.

8. Quark/Lepton Substructure

Given the layers of structure observed previously, it is natural to conjecture that quarks and leptons might be composites of more elementary constituents bound by a new interaction at some mass scale Λ. The masses and mixings would then be generated by the new dynamics, and one would have unknown new effects at the scale Λ. The dominant consequence for $Q^2 \ll \Lambda^2$ is new four-fermion interactions between interactions sharing constituents:[50]

$$\mathcal{L}_I = \frac{4\pi}{\Lambda^2}\,\bar{f}\Gamma f\,\bar{f}\Gamma f$$

(The normalization is conventional and corresponds to a strong coupling at Λ.)

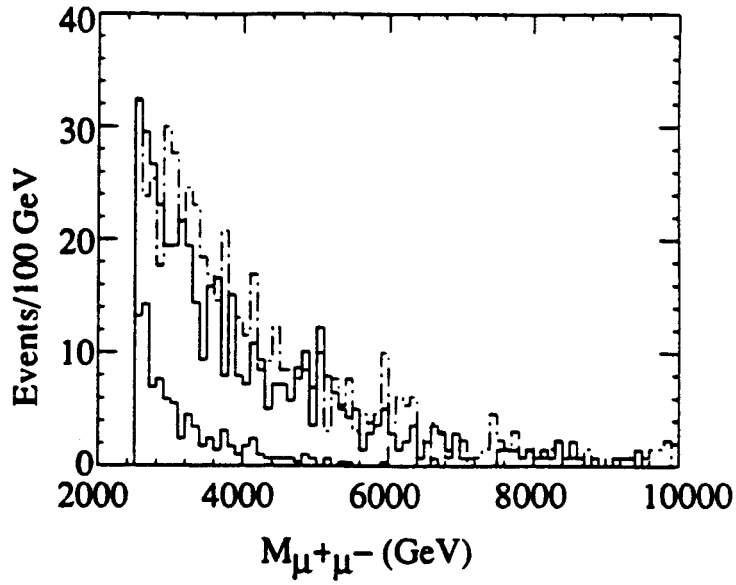

Figure 8.1: Drell-Yan cross section for standard model and for a compositeness interaction at $\Lambda = 20\,\text{TeV}$. (GEM)

Such interactions must minimally occur between identical quarks and leptons. Previous studies[23] have found that the jet cross section is sensitive to a scale $\Lambda \approx 20\,\text{TeV}$, compared to present bounds of order 1 TeV.

If the picture is to be at all attractive, then different fermions must share constituents. Hence one might expect four-fermion interactions in processes like $q\bar{q} \to \mu^+\mu^-$, even though these are model dependent. This measurement particularly benefits from higher luminosity, since the Drell-Yan cross section is small and lepton identification remains feasible. Fig. 8.1 shows the expected number of events per year at $\mathcal{L} = 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ for $\Lambda = 20\,\text{TeV}$.[4] Clearly, the sensitivity of the search is considerably better than this.

If compositeness were observed, it would be important to measure the $\mu^+\mu^-$ angular distribution, since this depends on the underlying dynamics. Fig. 8.2 shows the angular distribution for two possible models, one with helicity conservation and the other with an S-wave interaction.[4] Measuring this needs many events and emphasizes the gain from high luminosity.

9. Conclusion

The SSC will open up a qualitatively new mass scale. At this scale, we can plausibly expect to learn the origin of electroweak symmetry breaking, and we may also understand the origin of fermion masses. These are fundamental issues in particle physics, and ones on which little progress has been made since the SSC was first discussed in 1982.

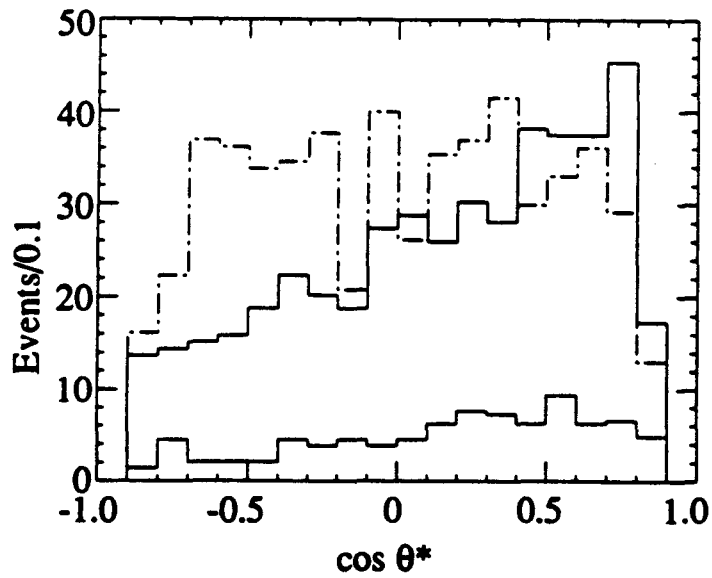

Figure 8.2: Drell-Yan angular distributions for standard model and for two different compositeness interactions at $\Lambda = 20\,\text{TeV}$. (GEM)

We do not know what the new physics may be. There are many possibilities, and it would be a surprise, perhaps even a disappointment, if any of the ones which have been discussed turned out to be the truth. But we do know that *any* new particle must either be stable, or decay into the quanta of the standard model, or decay into an unknown and therefore weakly interacting particle, giving missing energy. This means that we have some reasonable basis for designing detectors for the SSC and some hope that if those detectors can observe various hypothetical signatures, they can also detect what is actually there.

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