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# EXPERIMENTS AT FUTURE HADRON COLLIDERS

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## ABSTRACT

This report summarizes signatures and backgrounds for processes in high-energy hadronic collisions, particularly at the SSC. It includes both signatures for new particles — $t$ quarks, Higgs bosons, new $Z'$ bosons, supersymmetric particles, and technicolor particles — and other experiments which might be done. It is based on the 1990 Snowmass Workshop and on work contained in the Expressions of Interest submitted to the SSC.



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# EXPERIMENTS AT FUTURE HADRON COLLIDERS*

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ABSTRACT

This report summarizes signatures and backgrounds for processes in high-energy hadronic collisions, particularly at the SSC. It includes both signatures for new particles — $t$ quarks, Higgs bosons, new $Z'$ bosons, supersymmetric particles, and technicolor particles — and other experiments which might be done. It is based on the 1990 Snowmass Workshop and on work contained in the Expressions of Interest submitted to the SSC.

## I. INTRODUCTION

Since a 40 TeV hadron collider was first seriously discussed at the 1982 Snowmass Workshop[1], the standard model has been confirmed with ever increasing precision[2], but there is still no understanding of why it works so well or of how the electroweak symmetry is broken and particles acquire their masses. It seems increasingly likely that the answers to these questions lie at the 1 TeV mass scale[3]. Probing this scale will require much higher energies, which the SSC will provide. It will also require detectors which can separate small signals from much larger backgrounds. Fortunately the standard model provides us with the tools to understand both the potential signals and their backgrounds, at least approximately. The effort to do this was also begun at the 1982 Snowmass Workshop[1], and it has continued ever since.

The effort to understand the signatures and backgrounds has intensified with the call for Expressions of Interest (EoI) by the SSC Laboratory. Thirteen EoI's have been received, including four for large, general-purpose detectors aimed primarily at searching for new high mass physics and three to study to study $CP$ violation and rare decays for $B$ mesons. The four general-purpose proposals are in alphabetical order:

EMPACT: This detector[4] has a transition radiation detector (TRD) for tracking and electron identification, good electromagnetic and hadronic calorimetry, and air core toroid magnets to measure muons well over $|\eta| < 2.5$.

L*: This detector[5] has a small silicon tracker, high precision electromagnetic calorimetry, and hadron calorimetry inside of a very large, 0.75 T solenoid to measure muons precisely in the central region.

SDC: This detector[6] emphasizes vertex detection and straw tube tracking inside a 2 T solenoid. Outside the solenoid it has electromagnetic and hadronic calorimetry and iron for muon identification.

TEXAS: This detector[7] emphasizes calorimetry with a very large radius. It has scintillating fiber tracking inside and a TRD outside for muon momentum measurement.

Since the Snowmass meeting, the Program Advisory Committee of the SSC has met and has decided to consider at this time only proposals for two large, general-purpose experiments which are intended to be "competitive and complimentary." Also, the EMPACT and TEXAS collaborations have merged, leaving three candidates (EMPACT/TEXAS, L*, and SDC) for these two experiments, although new ones might still be submitted. At the request of the PAC, all of the detectors are being reduced in scope, so even the brief descriptions given above will soon change. The more specialized experiments generally require less lead time and so may be considered later.

This report is a review of the working group on SSC experiments at the 1990 Snowmass Workshop, including work done there in response to questions from the SSC Program Advisory Committee and work done previously for the Expressions of Interest. As such, it almost totally ignores the physics potential of the LHC, although the LHC could do a substantial fraction of the physics discussed here. It focuses heavily on the search for new particles and so perhaps underrepresents the interest in other possible kinds of physics. It also ignores detector development, although this is crucial for doing experiments in the SSC environment.

## II. WHAT IS NEW?

The list of possible physics signatures at the SSC has not changed substantially since the early Snowmass meetings, but there have been several significant experimental developments recently which have impor-

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tant bearings on the detailed expectations.

The top quark is heavy. Assuming the standard decays, CDF has published a limit[8]

$$m_t > 89\,\mathrm{GeV} \quad \mathrm{(CDF)}.$$

The model-independent LEP limit is $m_Z/2$. This affects the Higgs production cross section and decay modes, and it changes the $t\bar{t}$ backgrounds for many processes.

The standard model works extraordinarily well. In particular LEP and CDF have determined the $W$ and $Z$ masses with good precision:

$$\begin{aligned} m_W &= 79.78 \pm .33 \pm .26 \pm .36\,\mathrm{GeV} \quad &\mathrm{(CDF[9])}. \\ m_Z &= 91.172 \pm .031\,\mathrm{GeV} &\mathrm{(LEP[10])}. \end{aligned}$$

These are in excellent agreement with standard model predictions and give no evidence for new physics. One can even use the standard model radiative corrections to the $W$ and $Z$ masses to estimate the $t$ mass[2]:

$$m_t \approx 135 \pm 45 \pm 20\,\mathrm{GeV}.$$

If the central value is correct, then $t$ cannot be studied at LEP-200, and it becomes a subject for the SSC.

There are no light Higgs bosons. For the standard Higgs, the limits from LEP are[11]

$$m_H > 40\,\mathrm{GeV}$$

There are also bounds on Higgs bosons in supersymmetric models. At least for the minimal supersymmetric model, these provide significant constraints[12].

More generally, no new physics has been found so far at LEP. The $Z$ width implies just $N_\nu = 3$ light neutrinos[10]. All the LEP experiments agree that there are no SUSY particles, no technicolor particles, and no other phenomena beyond the standard model. It of course remains possible that new effects will be discovered as more events are accumulated.

In addition to these experimental results there are also some new theoretical ideas with direct bearing on SSC physics.

A $t\bar{t}$ condensate produced by some new interaction at a very high scale might generate the Higgs dynamically[13][14], with $m_H(\mu) = 2m_t(\mu)$ at the high scale $\mu$. One must then use the renormalization group to determine the actual particle mass, i.e. $m_H(m_H)$; this will always satisfy $m_H < 2m_t$. This scenario is identical to the minimal standard model for all scales $Q \ll \mu$. It is by no means compelling, but it does make a standard Higgs seem somewhat less unlikely.

There has been a revival of technicolor models using the idea of "walking technicolor" to suppress the unwanted flavor changing neutral currents[15]. While there is no good model, the signatures[16] are likely to be similar to the old technicolor models, except that the very light pseudo-Goldstone bosons become heavier.

Finally, it has been realized that the SSC will probably be capable of delivering $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ after a few years, and some serious thought is being given to using such luminosities, at least for some limited range of physics.

## III. GENERAL REQUIREMENTS

The general impression from the largely negative new experimental results is that any new physics is likely to be at high mass, e.g. at the electroweak scale,

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

There is a wide range of possible new particles and mass scales. But any new particle must decay into the quanta of the standard model and/or into particles which are weakly coupled to known particles: jets, $e$, $\mu$, and $\tau$ leptons, prompt photons, $W$'s and $Z$'s, and non-interacting particles giving $p_{T,\mathrm{miss}}$. Since heavy quarks are less common than ordinary jets, it is also useful to be able to identify $b$'s. In general new particles will decay into more than one different kind of object, so a detector which can observe all of them has a major advantage.

For masses on the order of $v$ or greater, the decay products will have high $p_T$ and be central in $\eta$. For typical signals the following ranges are probably adequate:

$$\begin{array}{lll} p_T \gtrsim 15\,\mathrm{GeV}, & \eta \lesssim 3 & \text{for leptons} \\ p_T \gtrsim 25\,\mathrm{GeV}, & \eta \lesssim 3\text{–}4 & \text{for jets} \\ p_T \gtrsim 50\,\mathrm{GeV}, & \eta \lesssim 5.5 & \text{for } p_{T,\mathrm{miss}} \end{array}$$

While large $\eta$ coverage is necessary for $p_{T,\mathrm{miss}}$, the resolution is dominated by nongaussian tails from cracks or other effects. Since backgrounds are often large, good resolution and multiple signatures are essential.

Inclusive trigger levels certainly cannot be set at such low levels, but a multilevel trigger, probably with three levels, appears to be feasible[4][5][6]. Level I would reduce the rate to roughly $10^4\,\mathrm{sec}^{-1}$. This can be done by triggering on muons, electromagnetic clusters, and hadronic clusters with

$$\begin{array}{ll} p_T \gtrsim 10\,\mathrm{GeV}, & \text{for muons} \\ p_T \gtrsim 25\,\mathrm{GeV}, & \text{for e.m. clusters} \\ p_T \gtrsim 100\,\mathrm{GeV}, & \text{for jets} \end{array}$$

Level II would refine the Level I trigger and provide coincidences among its various components. Level III would be based on a powerful online parallel computer able to make more complex decisions.

The general philosophy of measuring all the standard model signatures has been followed by all four of the high-$p_T$ EoI's, although they have differing emphasis. But there may also be a role for specialized detectors; BCD and $10^{34}$ are possible examples.

## IV. PHYSICS BENCHMARKS

The idea of defining a list of processes with which to judge the potential of an accelerator or a detector goes back at least to the 1982 Snowmass meeting[1]. The objective is not to cover all possible processes but to find a representative list which tests all the important issues. (At Snowmass 1982 these processes were called "bellwethers;" hopefully the list of processes will not be followed in too sheep-like a fashion.)

The basic benchmark list for high-$p_T$ physics at the SSC has changed very little since 1984[3]. It includes

- Top
- Higgs
- $WW$ interactions
- New $W$'s, $Z$'s
- Compositeness
- Technicolor
- SUSY

Of course there have been many detailed changes both in the signatures and in the understanding of the backgrounds. There are also several processes with low or intermediate $p_T$ which are of interest. The rest of this article will review work on all of these topics done for the various EoI's and in the working groups.

## V. TOP

While the discovery of the top is likely at the Texan, detailed measurements of its properties will need the SSC; LEP-200 is almost excluded by the current CDF mass limit[8]. If the top mass is close to the upper limit of about 200 GeV, so that it is not found at the Texan, then it is trivial to discover at the SSC by measuring the rate for isolated $e\mu$ events. The only real physics background comes from $q\bar{q} \to W^+W^-$ events, which have a much smaller cross section.

*t Mass:* The top mass could be important, since the $t$ may play unique dynamical role. The simplest way to determine the mass is to measure the cross section

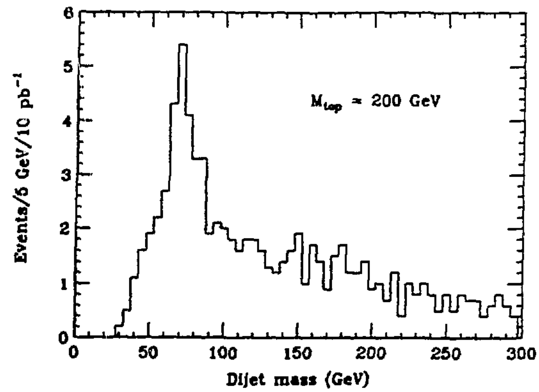


Figure 1: Reconstructed $W \to q\bar{q}$ mass using $b$ tagging. (SDC)

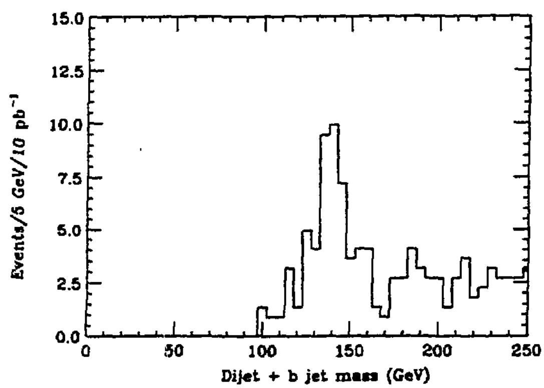


Figure 2: Reconstructed $t \to Wb$ mass using $b$ tagging. (SDC)

for isolated $e\mu$ events. This cross section is probably calculable to ~50%, including both uncertainties in the perturbative QCD cross section[17] and uncertainties in the effects of cuts on the $e$ and $\mu$ acceptance. This would determine the mass to ~10% assuming standard model decays. Note that

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

so that high statistics are available.

To trigger on a $t\bar{t}$ event it is probably necessary to require a $t \to \ell\nu b$ decay. For the other $t$, one can reconstruct the $W \to q\bar{q}'$ decay and the $Wb$ mass in

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

SDC[6] has studied this and finds that tagging $b$ jets

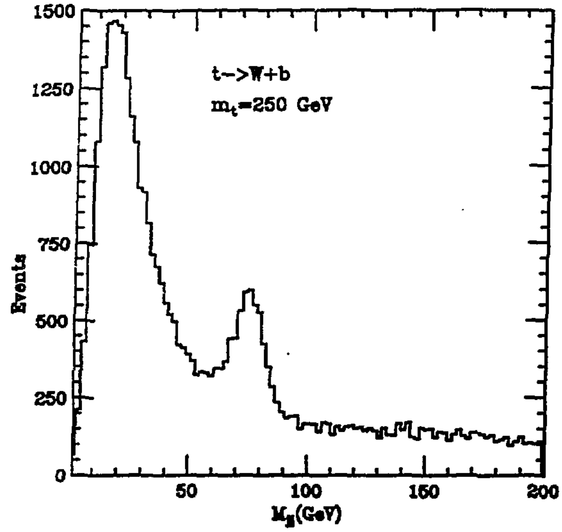


Figure 3: Reconstructed $W \to q\bar{q}$ mass without $b$ tagging. (L*)

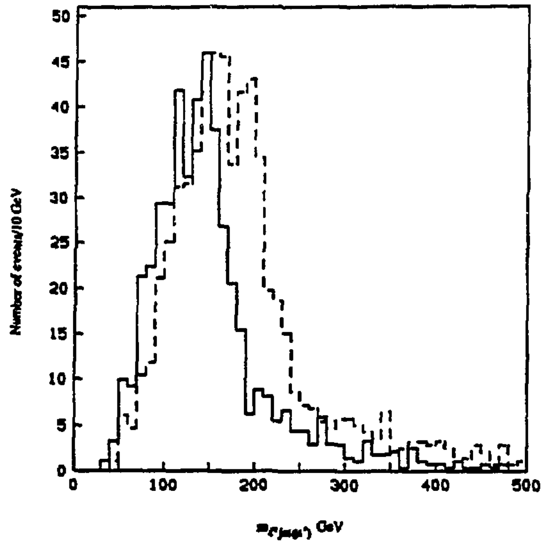

Figure 4: $M(\ell_1 b)$ from $t$ decays for $m_t = 200\,\mathrm{GeV}$, $250\,\mathrm{GeV}$. (EMPACT)

with a vertex detector is necessary to reduce the combinatorial background. The resulting distributions are shown in Fig. 1, 2. But L*[5] finds that $b$ tagging is not needed: after cuts on $p_{T,\mu}$ and $p_{T,\mathrm{miss}}$, the mass distribution including all jets with $E_{\mathrm{jet}} > 50\,\mathrm{GeV}$ for $30° < \theta < 150°$ also shows a signal, as can be seen in Fig. 3. While $b$ tagging is clearly useful, the question of whether it is crucial deserves more study.

Given the high statistics available at the SSC, it is not essential to reconstruct the mass; instead one can measure the distribution of a quantity which does not have a narrow peak but which depends on $m_t$ in a known way. This may give smaller systematic errors and so a more precise value for $m_t$, particularly for quantities which do not involve jets. Three such quantities are obvious candidates:

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

The last of these, $M(\ell_1\ell_3)$, is potentially the most precise, since it is independent of any measurements of hadronic jets and depends mainly on $f_{b\to\mu}(x,Q^2)$, but $M(\ell_1 b)$ is more sensitive to $m_t$. The distribution from EMPACT[4] of an isolated lepton plus a $b$ jet tagged with a muon is shown in Fig. 4. The statistical error on this method is tiny. The systematic error is determined by the sensitivity to the production distribution of the $t$ and the uncertainty in this. If the $t$'s are produced at higher $p_T$, then more of the leptons and jets will pass a minimum-$p_T$ cut, and the mass will shift to lower values. From the distribution for various bins of $p_{T,t}$ it is estimated[19] that the systematic limit is a few GeV.

*t Decays:* There are no interesting decays in the standard model. It is important to verify that $t \to Wb$ to make sure that the new quark is indeed a $t$. This requires observing the $b$ vertex and/or detecting a non-isolated $\mu$ in the $b$ jet. Measuring $t \to Ws$ at the expected rate appears impossible.

Beyond the standard model the $t$ has many possible decays. A very plausibie extension of the standard model is the existence of more than one Higgs doublet[18]. This implies the existence of charged Higgs bosons; if the $H^+$ lighter than the $t$, then a substantial branching ratio for

$$t \to H^+ b, \quad H^+ \to \tau^+\nu$$

is expected[18]. If the $t$ is heavier than the $W$, then the conventional $W$ decay will still have a substantial branching ratio, so one can trigger on

$$\bar{t} \to W^-\bar{b} \to \ell^-\bar{\nu}\bar{b}.$$

Since the $\tau$ has a substantial branching ratio into one-prong hadronic jets, one can search for this mode by measuring the ratio of one-prong jets to leptons. This

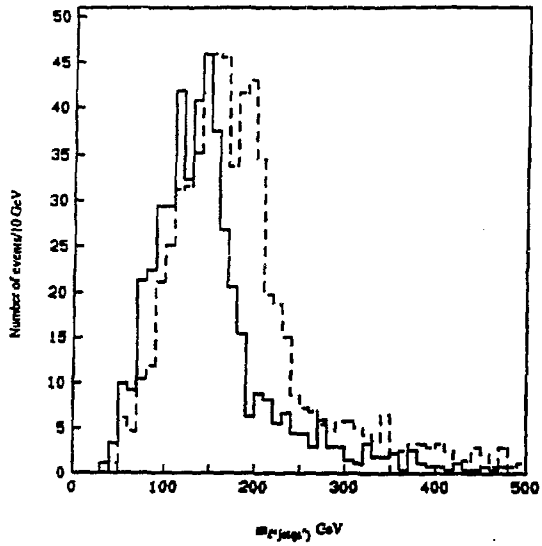


Figure 5: Reconstructed $H^{\pm} \to jj$ produced from $t\bar{t}$ pairs. The other $t$ provides a leptonic tag. (L*)

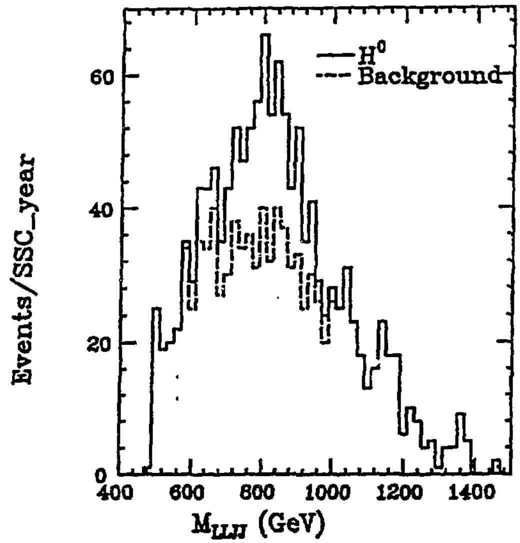


Figure 6: Reconstructed $H \to \ell^+\ell^- q\bar{q}$ mass. (L*)

has been analyzed by all of the EoI groups. The $\tau$ misidentification seems small.

It is possible although unlikely that $H^+ \to c\bar{s}$ dominates. In this case one can check the $t \to \ell X$ branching ratio, study the jet distributions, or reconstruct $M(H^+ \to jj)$. The mass reconstruction analysis by L* is shown in Fig. 5. The background in this figure comes from wrong combinations of jets.

In the standard model the polarization of the $W$ from $t$ decay is predicted, and the longitudinal polarization becomes large because the $W_L$ couples strongly to heavy particles:

$$\frac{\Gamma_L}{\Gamma_T} = \frac{m_t^2}{2m_W^2}$$

One can measure the $W \to \ell\nu$ polarization by measuring the $\ell b$ mass[19]. This distribution is also sensitive to the $t$ mass. Measuring it well requires good acceptance both for leptons and for jets.

There are several other possible nonstandard decays for $t$ quarks:

$$t \to Z^0 c$$
$$t \to \tilde{t}\tilde{\chi}_1^0$$
$$t \to W^+ s?$$

Of these, a useful measurement of the Cabibbo suppressed mode $t \to Ws$ appears to be the most difficult. None of these modes has an obvious effect on detector design.

## VI. HIGGS

The standard model with a light Higgs boson is unnatural[20] in presence of high mass scales such as those associated with grand unification or gravity. But the idea[13][14] that a $t\bar{t}$ condensate might generate an effective Higgs boson at least raises the possibility that the standard model might be valid up to mass scales $\Lambda \gtrsim 10^{15}\,\mathrm{GeV}$. LEP has established an experimental lower limit of 40 GeV for the standard Higgs mass. Numerical studies of the standard model on the lattice have given an upper limit[21]

$$m_H \leq 650\text{–}800\,\mathrm{GeV}$$

This is a refinement of the old upper limit $m_H \leq 1\,\mathrm{TeV}$ from perturbative unitarity[22].

Even though the standard Higgs is not very plausible theoretically, it remains the most studied benchmark for detectors at the SSC. The signatures are quite different for a heavy Higgs ($2m_Z < m_H \lesssim 800\,\mathrm{GeV}$), an intermediate mass Higgs too heavy to be found at LEP-200 ($80\,\mathrm{GeV} < m_H < 2m_Z$), and a very heavy Higgs ($m_H \gtrsim 800\,\mathrm{GeV}$).

*Heavy Standard Higgs:* For $m_H > 2m_Z$ the cleanest decay mode is $H \to Z^0 Z^0 \to \ell^+\ell^-\ell^+\ell^-$ where $\ell = e, \mu$. This mode has been beaten to death, particularly in the 1987 Berkeley Workshop[23]. The experimental signature is very clean, and there is very little background, at least if the $Z \to \ell^+\ell^-$ mass resolution is

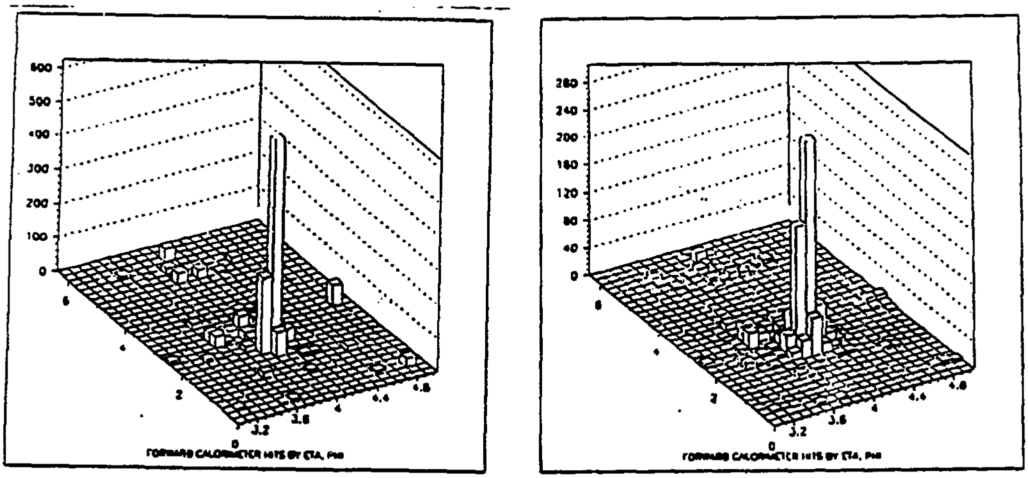

Figure 7: Simulation of forward quark jet from $W^+W^- \to H$. Left: Generated event. Right: Same event after shower spreading. (TEXAS)

comparable to the $Z$ width. The only limitation on this mode is the low statistics for $m_H \gtrsim 600\,\mathrm{GeV}$ resulting from the small $Z \to \ell^+\ell^-$ branching ratio.

The statistics can be improved somewhat by including $H \to Z^0Z^0 \to \ell^+\ell^-\tau^+\tau^-$, which doubles $4\ell$ rate. This mode can in principle be fully reconstructed by fitting for the $\tau$ momenta using $\vec{p}_{T,\mathrm{miss}}$ and $m_Z$. About 60% of these events have at least one leptonic decay of a $\tau$, and the background for events with three isolated leptons plus one low-multiplicity jet must be very small. The remaining events have two leptons plus two low-multiplicity jets and probably are also quite clean. The experimental requirements to detect low-multiplicity jets and to measure the missing $\vec{p}_T$ with sufficient precision need further study.

The mode $H \to Z^0Z^0 \to \ell^+\ell^-\nu\bar{\nu}$ gives six times the $4\ell$ rate[24]. In this channel there is a large potential background from $Z^0$+jets where the jets are somehow missed. It is known[23] that this background can be rejected with a perfect detector covering $|\eta| \lesssim 5.5$. The background is not increased very much if one takes into account dead material in the calorimeter but still assumes Gaussian resolution. Non-Gaussian tails could be a problem. For example, to obtain adequate $\eta$ coverage it is necessary to make a transition at $\eta \approx 3$ between the forward calorimeter and the plug. A very crude estimate[25] concluded that this transition would produce about 10 times the $p_{T,\mathrm{miss}}$ cross section as an ideal detector. A better calculation of the effects of this transition using GEANT with full truncated showers has been started[26] and seems to be giving encouraging results. While it is probably possible to veto events with large $E_T$ near the transition, careful design of such transition regions is crucial.

The $H \to Z^0Z^0 \to \ell^+\ell^-q\bar{q}$ has a considerably larger branching ratio but also a large background from $Z^0$+jets. Several previous analyses[27][28][29], mainly for $H \to W^+W^- \to \ell^\pm\nu q\bar{q}$, have found that a cut on the $q\bar{q}$ mass alone gives $\Delta M \sim \pm 5\,\mathrm{GeV}$ and a signal/background ratio $S/B \approx 1/10$. A new analysis by L* requires $p_{T,Z} > 240\,\mathrm{GeV}$ and selects two jets in $\Delta\phi = \pm 50^\circ$ from $Z^0$. This analysis finds 210/640 events, as shown in Fig. 6, rather better than before and statistically significant if the background is well understood. Unfortunately the signal and background peak in the same place.

Several ideas have been suggested to improve the signal/background ratio in this channel. First, one can use a variety of jet shape variables[27] to try to distinguish $Z \to q\bar{q}$ from QCD jets. This is helped by the fact that for a heavy Higgs the $Z$ is longitudinally polarized, so the $q$ and $\bar{q}$ jets tend to have equal energy. Second, one can try to tag the forward jets which result in the $WW$ fusion process for Higgs production[30]. The $W$'s are radiated from quarks, $q \to Wq'$, with a bremsstrahlung-like spectrum, resulting in energetic $q'$ jets with $p_T \sim m_W$ and $\eta \gtrsim 3$. This appears quite promising: TEXAS finds that 35% of the signal and only 8% of the background events have a jet with $E_{\mathrm{jet}} > 1\,\mathrm{TeV}$ and $3 < \eta < 4.5$. A typical simulated event is shown in Fig. 7. Third, one can make a multiplicity cut, exploiting the fact that in $WW$ fusion the partons are off-shell by $\mathcal{O}(m_W)$ rather than $\mathcal{O}(m_H)$ and so radiate fewer gluons[31]. This is certainly qualitatively correct, but its quantitative effectiveness depends on soft physics. Given these additional handles, there is some cause for optimism. Even if this mode proves to be impossible, the ability to reconstruct $Z^0 \to q\bar{q}$ is still important, since it may be useful in other channels with less severe backgrounds.

Most studies have found that the $Z \to q\bar{q}$ width is not very sensitive to the resolution or the segmentation provided that $\Delta\eta = \Delta\phi \sim 0.05$. The new L* analysis finds somewhat greater sensitivity of the $S/B$ ratio to the resolution, perhaps because a better cluster algorithm has been used.

*Intermediate Mass Standard Higgs:* If $80\,\mathrm{GeV} < m_H < 2m_Z$, then the Higgs is observable neither at LEP-II nor in the relatively easy $Z^0Z^0$ channels. Then if $m_H < 2m_t$, as seems likely from the CDF bound on $m_t$, the dominant decay $H \to b\bar{b}$ is overwhelmed by QCD backgrounds. But the rare decay $H \to \gamma\gamma$ has a branching ratio of order $10^{-3}$, large enough to be useful[32]. The irreducible background comes from the QCD processes like $q\bar{q} \to \gamma\gamma$ and $g + g \to \gamma + \gamma$ and requires

$$\frac{\Delta M}{M} \lesssim 1\%$$

This implies both a high resolution electromagnetic calorimeter and measurement of the vertex position to $\mathcal{O}(1\,\mathrm{cm})$. The signal and background are shown in Fig. 8 for a resolution which might be obtained with a $BaF$ calorimeter. The signals are statistically significant except perhaps near 80 GeV, although the signal to background ratio is quite poor even with the very good resolution.

TEXAS has suggested that this measurement can also be done using a fine sampling calorimeter. The resolution is not quite as good, but it is adequate at least for higher masses, as can be seen from Fig. 9.

In addition to this irreducible background there is also backgrounds from the QCD $\gamma$ + jet and jet + jet processes. Eliminating these requires a $\gamma$/jet rejection of $\sim 10^{-4}$. This has been studied by L* using a detailed simulation and found to be obtainable. A crude estimate may shed some light on the detailed analysis. Take for the jet $\to \pi^0$ fragmentation function the form

$$f(x) = \frac{p+1}{3}\frac{(1-x)^p}{x}$$

with $p \gtrsim 2$, normalized so that $\int dx\, x f(x) = 1/3$. Then the probability to get a single $\pi^0$ with a momentum fraction $\geq x$ is

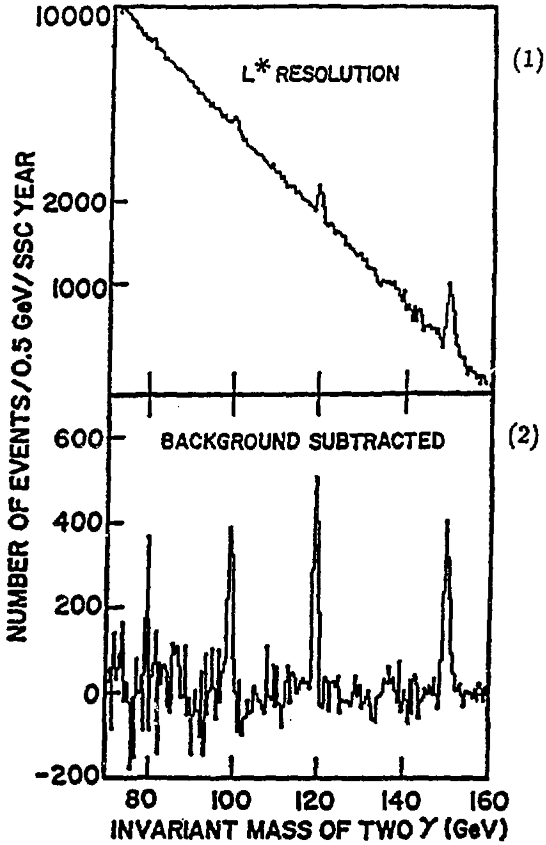


Figure 8: Top: Signal plus background for $H \to \gamma\gamma$. Bottom: Background subtracted signal for with $BaF_2$ calorimeter. (L*)

$$P \approx \frac{1}{3}(1-x)^{p+1}.$$

Since $p = 2$ is appropriate only for quark jets at low $Q^2$ and $p > 2$ otherwise, it appears possible to get the required rejection provided that one can make an isolation cut at $x > 0.9$. But the effectiveness of the cut degrades rapidly if one must reduce the $x$ cut, e.g. because of noise or pileup.

The ratio of signal to background in the $\gamma\gamma$ channel is not reliably known. The $g + g \to \gamma + \gamma$ process, a gauge-invariant subset of the $\mathcal{O}(\alpha_s^2)$ corrections, is substantially larger than the lowest order $q\bar{q}$ process and has been included, but many other unknown $\mathcal{O}(\alpha_s)$

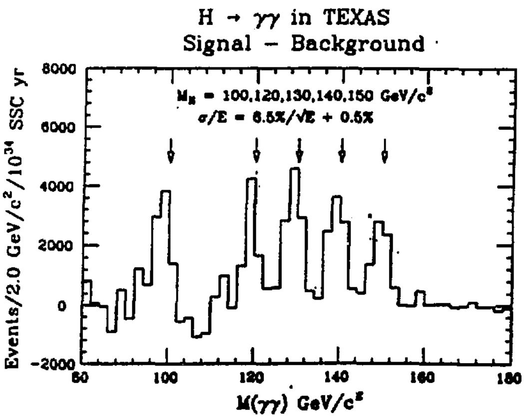


Figure 9: Background subtracted signal for $H \to \gamma\gamma$ with fine sampling calorimeter. (TEXAS)

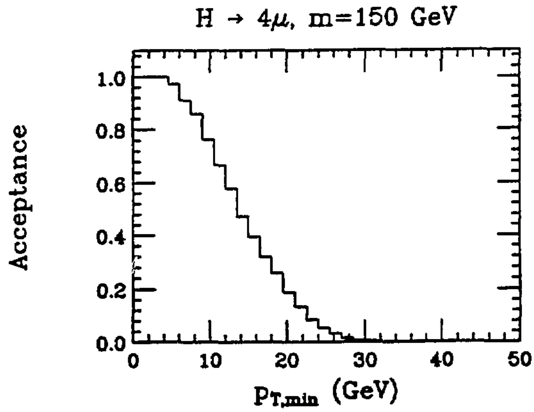


Figure 10: Minimum $p_{T,\ell}$ for $H \to Z^0Z^{0*} \to \ell^+\ell^-\ell^+\ell^-$. (EMPACT)

and $\mathcal{O}(\alpha_s^2)$ are omitted. Likewise, a reduction by about a factor of 2 in $\Gamma(H \to b\bar{b})$ from the running of the $b$-quark mass has been included, but higher order QCD corrections to the cross section are not known. The theoretical uncertainty is not particularly worse in this channel than in others, but it is more critical here because the signal to background ratio is so poor.

$H \to Z^0Z^{0*} \to \ell^+\ell^-\ell^+\ell^-$ is also a possible decay mode for searching for an intermediate mass Higgs[32]. This mode has an adequate branching ratio for $m_H \gtrsim 140\,\mathrm{GeV}$. It requires detection of low-$p_T$ leptons, as shown in Fig. 10. Since a Higgs in this range is very narrow, good mass resolution is important, although the background shown in Fig. 11 is moderate.

The associated production process, $W^\pm + H \to \ell^\pm\nu + b\bar{b}$, might be observable, but it appears very difficult[33], particularly if one takes into account backgrounds from $t\bar{t}$. A more promising associated production mode is $W^\pm + H \to \ell^\pm\nu\gamma\gamma$[34]. This needs less $\gamma\gamma$ resolution than $H \to \gamma\gamma$, but it has a tiny rate. More study is needed, particularly to see if this mode could be detected at $\mathcal{L} \gg 10^{33}\,\mathrm{cm^{-2}sec^{-1}}$.

*Nonstandard Higgs:* Nonstandard Higgs bosons from more than one Higgs doublet are nonstandard but not very unlikely. Supersymmetric models provide the most plausible framework for elementary Higgs bosons, and they require at least two Higgs doublets. In the minimal SUSY model the lightest Higgs boson must have $m_h < m_Z$ and so should be found by LEP-180. But trivial generalizations of the minimal model allow the masses to be heavier.

Two-doublet Higgs models give charged Higgs bosons. A possible signature for charged Higgs $H^+$ is

$$\begin{array}{l} g + b \to H^- + t \\ \qquad\quad \downarrow \\ \qquad W^- + h^0 \\ \qquad\quad \downarrow \\ \qquad \ell^-\bar{\nu} + b\bar{b} \end{array}$$

The backgrounds for this signature have not been analyzed, but $b$ jet tagging is clearly important. Two-doublet models also give a $CP = -1$ neutral Higgs boson $A$. A possible signature for this is

$$\begin{array}{l} g + g \to A \\ \qquad\quad \downarrow \\ \qquad Z^0 + h^0 \\ \qquad\quad \downarrow \\ \qquad \ell^+\ell^- + b\bar{b} \end{array}$$

Again the backgrounds have not been analyzed.

## VII. NEW $W'$ AND $Z'$

An gauge group larger than $SU(3) \times SU(2) \times U(1)$ is natural in several theoretical frameworks and in any case is an obvious extension of the standard model. A rather general possibility is[35]

$$E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\theta$$

with an $E_6$ group breaking down to give one extra $Z'$ with unknown mass and mixing angle $\theta_{E6}$. The width

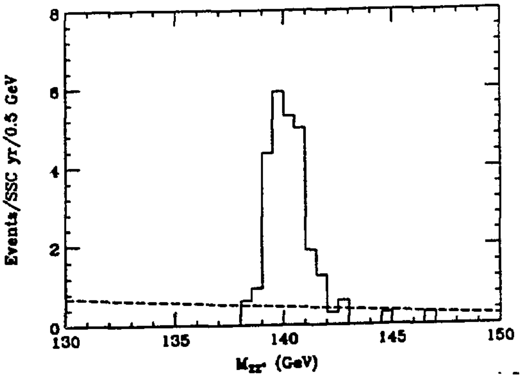


Figure 11: Reconstructed mass for $H \rightarrow Z^0 Z^{0*} \rightarrow \ell^+\ell^-\ell^+\ell^-$ and estimated background. (SDC)

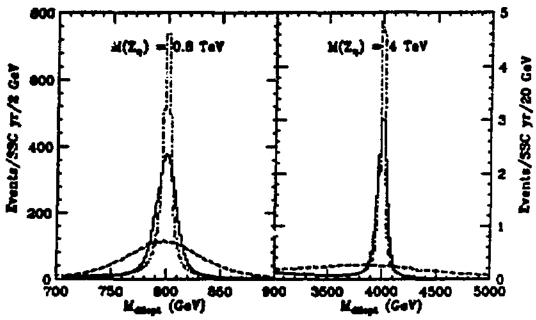


Figure 12: Dash-dot curve: $Z'$ signal plus Drell-Yan background. Solid: With $e^+e^-$ resolution. Dashed: With $\mu^+\mu^-$ resolution. (SDC)

of the new $Z'$ is expected to be

$$\frac{\Gamma}{M} = 0.5\%\text{–}3\%$$

depending on what if any exotic decay modes of the $Z'$ are possible.

Discovery of a $Z'$ in its $e^+e^-$ and $\mu^+\mu^-$ decay modes is very clean, as can be seen in Fig. 12. Masses $M \sim 6\,\text{TeV}$ could be detected in a standard SSC year[3]. This process probably sets the upper limit of the dynamic range for electromagnetic calorimetry, and measuring the muons from a heavy $Z'$ poses a formidable challenge for the muon system. Good acceptance requires measuring the leptons for $|\eta| \lesssim 2.5$.

The forward-backward asymmetry combined with the observed rate $B\sigma$ can be used to determine the

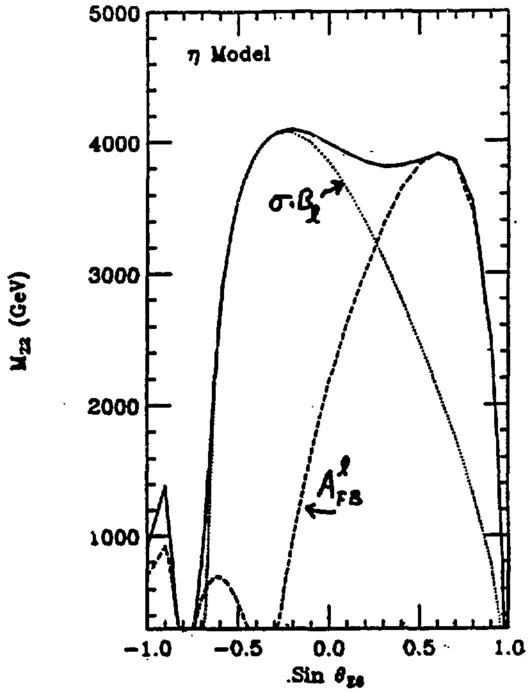


Figure 13: Determination of $\theta_{E6}$ from production cross section and forward-backward asymmetry.

mixing angle $\theta_{E6}$ with reasonable precision. This is illustrated for the case of $Z_\eta$ with $\sin\theta_{E6} = -\sqrt{5/8}$ in Fig. 13. The plot shows the regions of the $M_{Z'}$–$\theta_{E6}$ plane which are excluded at 95% confidence using the observed rate and the forward-backward asymmetry for $\eta < 2.5$. Only a small region around the assumed value of $\theta_{E6}$ survives for masses less than about 4 TeV. In $pp$ collisions the asymmetry vanishes at $y_Z = 0$ by symmetry, so it is essential to measure leptons for at least $y \lesssim 2.5$, but the asymmetry measurement improves only slowly beyond that.

## VIII. TECHNICOLOR

Technicolor models[36] replace the elementary Higgs fields with dynamical bound states of new spin-1/2 techniquarks bound by a new interaction which becomes strong at $\Lambda \sim 1\,\text{TeV}$. Generally technicolor resembles QCD with the longitudinal components of the $W^\pm$ and $Z^0$ playing the role of the pions. The original models predicted too large flavor changing neutral currents, but the newer walking-technicolor scenario[15] has revived interest. However, there is still no good model. Technicolor models generally predict a rich

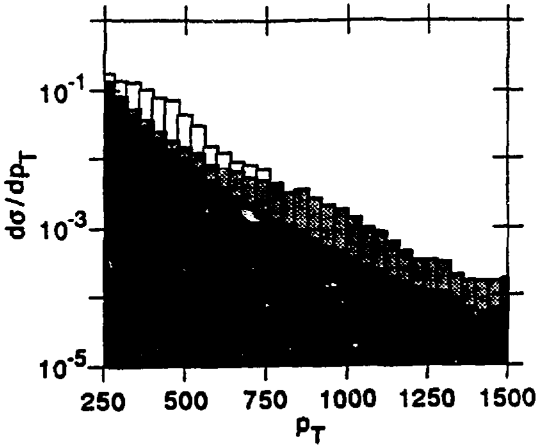


Figure 14: Cross sections for $\rho_{TC} \to \ell\nu\ell^+\ell^-$. (Ref. [37])

spectrum of new particles. Most of these particles have $m \sim \Lambda$, but there can also be pseudo-Goldstone bosons with $m \ll \Lambda$. Several different technicolor particles have been discussed in the EoI's and at this workshop[37].

$\rho^{\pm}_{TC} \to W^{\pm}Z^0$: The $\rho_{TC}$, the analog of the $\rho$ in QCD, is one of the more model-independent particles. It is produced both by $WW$ fusion and by mixing with the ordinary $W$. The masses is expected to be $m =$ 1–2 TeV, so the small cross sections are very small. However, there exist models which give much smaller masses.

Leptonic decays of the $W^\pm$ and $Z^0$ give very small numbers of events; see Fig. 14. One really needs to detect both $e$ and $\mu$ at $\mathcal{L} \sim 10^{34}$. This appears feasible but certainly needs more study. Also, it is important to understand whether $p_{T,\text{miss}}$ needs to be measured or whether it is sufficient to assume that the $W^\pm$ and $Z^0$ balance transverse momentum. The $\rho^0_{TC}$ decays only into $W^+W^-$ and so gives two missing neutrinos in the leptonic modes.

Hadronic decays of the $W^\pm$ or $Z^0$ would increase the branching ratio but have much more background. The situation is similar to that for the standard Higgs, and similar methods — a multiplicity cut or tagging of forward jets — might be effective for $WW$ fusion contribution to the cross section. The structure of the signal from $W$ mixing would be much more similar to the background.

$\omega_{TC} \to Z^0\gamma$: The $\omega_T$, the analog of the $\omega$, is also relatively model independent, and its decay into $Z^0\gamma$

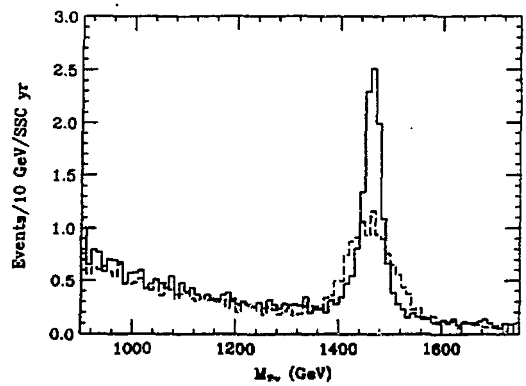


Figure 15: Cross sections for $\omega_{TC} \to \ell^+\ell^-\gamma$. (SDC)

gives a better signature than the $\rho_{TC}$. This signature has been studied by SDC. The cross section is very small, as can be seen in Fig. 15, so again operation at greater than standard luminosity would be important. Identification of single photons at very high $p_T$ is required, but it is probably sufficient to require an isolated electromagnetic cluster with no track pointing to it.

$P_3 \to \tau b$: In the older technicolor models there are light leptoquarks $P_3$ with masses $m = 160\,\text{GeV}$. These presumably decay into the heaviest lepton+quark pairs available, including $\tau + b$. The $P_3$ is a color triplet scalar which is pointlike up to scales of order $\Lambda$, so it is pair produced with cross section about 15% of that for a quark of same mass. The signature is two $\tau$'s plus two jets[16]. The event can be reconstructed in principle, neglecting the $\tau$ mass and using the measured $\vec{p}_{T,\text{miss}}$ to determine the sums of $\nu$ energies parallel to the observed $\tau$ directions. The resolution required to do this has not been determined, and it is not known whether a vertex detector is needed.

$P_8 \to t\bar{t}$: This pseudo-Goldstone boson is also model dependent; in the old models it has $m \sim 240\,\text{GeV}$. In many ways it resembles a Higgs but has a larger production cross section. The signatures and backgrounds for it were studied[38] for $m_t = 20\,\text{GeV}(!)$. With the current estimate of the $t$ mass, $m_{P_8} \sim 2m_t$, so the signatures are much different, and a new study is needed.

## IX. SUPERSYMMETRY

Supersymmetry[39] is perhaps the most plausible theoretical framework for elementary Higgs scalars. It is also a good example of a model with complex signatures. In general SUSY particles must be produced in pairs, and the lightest SUSY particle (LSP) is absolutely stable and weakly interacting. In the minimal SUSY model[39][12] there must be *at least two Higgs* doublets, giving three neutral and a pair of charged Higgs bosons. The superpartners of these mix with those of the photon, $W^{\pm}$, and $Z^0$ to give

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

The heavier $\chi_i$ decay into lighter ones plus $W^{\pm}$'s, $Z^0$'s, and even Higgs bosons, eventually leading to the LSP $\tilde{\chi}_1^0$ and giving the characteristic signature of missing transverse momentum.

SUSY masses might be expected to be of order the electroweak symmetry-breaking scale $v = 246\,\mathrm{GeV}$. In the minimal model one of the Higgs bosons must be lighter than the $Z^0$, so there are already significant limits on it from LEP[12]. CDF has also reported preliminary limits on gluinos and squarks assuming the simplest decay modes[12]. *Non-minimal models* are less constrained and in general have qualitatively similar signatures at SSC energies.

Detailed analysis of the experimental signatures for SUSY cascade decays at the SSC began at the 1988 Snowmass workshop[40][41]. The analysis has concentrated on *gluinos*, both because they have large cross sections and because their branching ratios are most affected by cascade decays. A "typical" 750 GeV gluino event might be:

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

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

This event contains seven undiscovered particles. Clearly there is a rich array of possible signatures.

*Missing $p_T$:* Gluino cross sections and decay modes are completely determined by perturbative QCD. The dominant production mechanism is

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

Since every gluino ultimately decays into the LSP $\tilde{\chi}_1^0$, which escapes from the detector, the most characteristic signature of SUSY is *missing* transverse momentum $E_{T,\mathrm{miss}}$. But the amount of $E_{T,\mathrm{miss}}$ *is reduced for cascade decays* compared to direct decays into $q\bar{q}\tilde{\gamma}$. The physics backgrounds come from QCD production of heavy quarks and of high-$p_T$ $W^{\pm}$ and $Z^0$.

High statistics studies of the $E_{T,\mathrm{miss}}$ signal with cascade decays and of the backgrounds have been done by

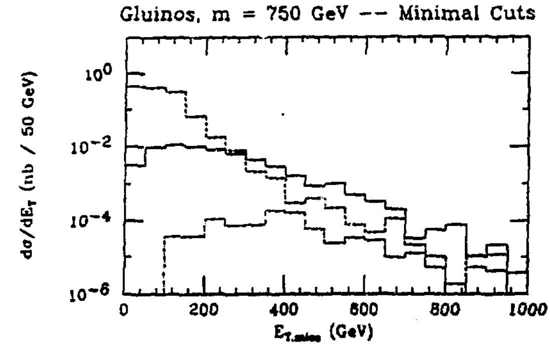


Figure 16: $E_{T,\mathrm{miss}}$ distributions for 750 GeV gluino and background after cuts. (EMPACT)

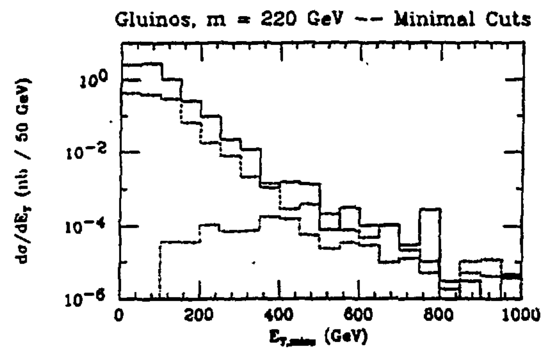


Figure 17: $E_{T,\mathrm{miss}}$ distributions for 220 GeV gluino and background after cuts. (EMPACT)

EMPACT and SDC. Since the gluinos are produced with $p_T \sim m_{\tilde{g}}$, their decay products are generally widely separated. Hence the background can be reduced by requiring several jets and large sphericity $S_T$ in the transverse plane, e.g.

$$n_{\mathrm{jet}} \geq 4$$
$$S_T \geq 0.2$$

With cuts like these, the signature *dominates over the* backgrounds for large $E_{T,\mathrm{miss}}$ over the whole mass range of interest. The signals for 220 GeV and 750 GeV gluinos and the backgrounds calculated using EMPACT resolution functions are shown in Fig. 16–17.

The analyses done so far have generally used Gaussian resolutions and fairly idealized detector geometries. Then the experimental resolutions have only

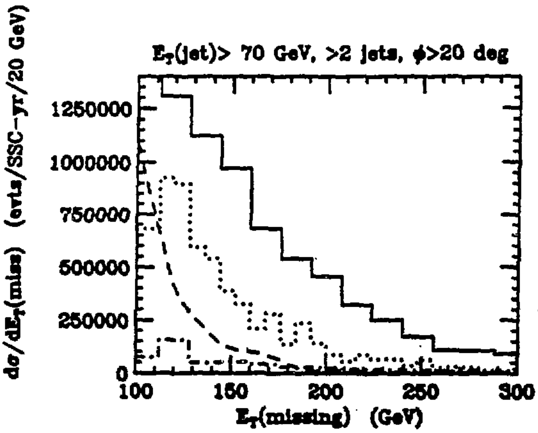


Figure 18: $E_{T,\rm miss}$ distributions. Solid: 300 GeV gluino. Dotted: heavy quark background. Dashed: Background from mismeasured jets using CDF data. Dash-dotted: $W$ and $Z$ background. (SDC)

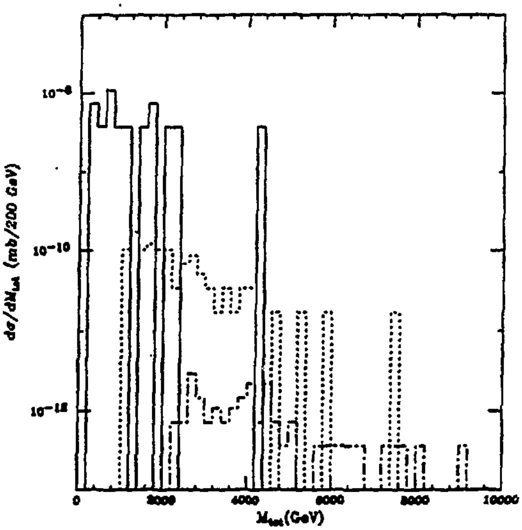

Figure 19: $M(\ell_1\ell_2jjjj)$ distributions for various gluino masses. (EMPACT)

small effects provided that the detector covers $|\eta| \lesssim 5.5$. Non-Gaussian tails could be more important. This has been estimated by SDC using the observed mismeasurement of jets in CDF and does not give a large effect, as can be seen in Fig 18. The spreading of hadronic showers from the transition at $\eta = 3$ may also be important. A calculation of this using GEANT is in progress[26], and the preliminary results seem quite encouraging.

*Multilepton signatures:* Since the $\tilde{g}$ is a Majorana fermion, it produces equal rates for $\ell^\pm\ell^\pm$ and $\ell^+\ell^-$ decays. The leptons are relatively hard and isolated, so they are easy to detect and there is little background from cascade decays of heavy quarks.

The gluino mass can be estimated by looking at the total mass $M(\ell\ell jjjj)$ of the two leptons and the four highest-$p_T$ jets, Fig. 19, or at the mass $M(\ell jj)$ of either lepton and the two nearest jets. Observing such a signal would be an important comfirmation of the Majorana nature of the gluino. For some range of parameters, particularly for heavy gluinos, decays involving $Z^0 \to \ell^+\ell^-$ can also be observable.

Since the gluino is a good example of a complex signature at the SSC, it would be worth while exploring whether $W$ branching ratios can be determined, e.g. from reconstructing $W \to q\bar{q}$, and how well $\tilde{\chi}$ masses can be measured. It is obviously also important to understand the real experimental limitations on the measurement of $E_{T,\rm miss}$.

## X. B PHYSICS

While the SSC is primarily intended to search for new heavy particles, it also copiously produces known particles. For $W^\pm$ and $Z^0$ decays, it seems unlikely that the SSC could be competitive with LEP. But for $B$ decays the advantage in rate over even future $e^+e^-$ machines is very large, since

$$\sigma_{b\bar{b}} \approx 500\,\mu\text{b},$$

giving $5 \times 10^{11}$ events for $\mathcal{L} = 10^{39}\,\text{cm}^{-2}\text{sec}^{-1}$. The long $B$ lifetime makes it possible to select $B$ decays with a vertex detector, and it also implies that the normal decays are suppressed, so that the branching ratios for rare phenomena are potentially much larger than for $K$ decays.

CP violation in $B$ decays is a possible probe of new interactions, but it is interesting even in the context of the standard model. The partial rate CP asymmetries for certain final states that are CP eigenstates, e.g. $B^0 \to \psi K_S$, $B^0 \to \pi^+\pi^-$, and $B^0 \to \rho^0 K_S$, are calculable in the standard model in terms of the CKM matrix elements and $m_t$ with no corrections from strong interactions. Furthermore, the asymmetries are estimated to be large, of order 10%, although the branching ratios for these modes are only $10^{-6}$–$10^{-5}$. Thus CP violation in these modes provides an important test of the standard model: understanding

Table 1: $B\bar{B}$ production at existing and proposed accelerators. (BCD)

| Accelerator | $\sqrt{s}$(TeV) | $\sigma(\mu b)$ | N/$10^7$ sec |
|---|---|---|---|
| TEV-II | 0.04 | 0.003 | $1.7 \times 10^7$ |
| SSC($p$–$Si$) | 0.2 | 3 | $2 \times 10^{10}$ |
| RHIC($p$–$p$) | 0.5 | 10 | $2.5 \times 10^{10}$ |
| TEV-I | 1.8 | 40 | $1 \times 10^{11}$ |
| LHC | 16 | 250 | $3.3 \times 10^{11}$ |
| SSC | 40 | 500 | $5 \times 10^{11}$ |

the CKM matrix is as important an aspect of the problem of mass generation as understanding the Higgs mechanism. CP-violaing asymmetries in other $B$ decay modes, such as those enumerated in the BCD Expression of Interest, are also interesting although less precisely calculable.

Given the small branching ratios, at least $10^8$ events are needed to have a hope of detecting CP violation in the $B$ system. This would require an $e^+e^-$ collider with a luminosity $\mathcal{L} \gtrsim 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, a formidable technical challenge. The potential $B$ production at various accelerators is summarized in Table 1. At the SSC, it is easy to produce enough $B$'s; the challenge is to detect them. The essential requirements for the detector are:

- A vertex detector capable of distinguishing charged tracks from the $B$ vertex and tracks from the primary vertex.
- Large $\eta$ coverage, since the $B$'s are produced with $\eta \lesssim 4$ and it is often essential to detect all
- Good tracking and mass resolution to minimize backgrounds and to distinguish $B_d$ and $B_s$ decays.
- Good particle and lepton identification, again to minimize backgrounds.

Perhaps the most difficult aspect of a $B$ detector at the SSC is to construct a suitable trigger. While $B$ events constitute about 0.5% of the total cross section, it is impossible to read out the detector for every event without reducing the luminosity, and hence the available sample of $B$'s, drastically. The $B$'s are produced with $p_T \sim m_b$, and a typical SSC event contains a jet with similar $p_T$, so high-$p_T$ triggers are not effective. Thus one must trigger on leptons with $p_T \sim 1\,\mathrm{GeV}$ or somehow use the vertex detector information in the trigger.

The BCD Collaboration[43] has submitted a proposal to study CP violation and rare $B$ decays at the SSC. The proposed detector has dipole magnets, a silicon microstrip vertex detector with both cylindrical and transverse elements so that particles are not measured with small angles of incidence, tracking, Cerenkov counters for particle identification, and electromagnetic calorimetry. This detector looks quite different from the general purpose ones, and it seems clear that a dedicated detector is needed to do $B$ physics optimally. Even though BCD was not approved for the initial round of SSC experiments, something like it remains an interesting idea to exploit a unique window to understand CKM physics in the standard model.

An interesting alternative to studying $B$ decays in 40 TeV collisions is to use an external 20 TeV proton beam on a fixed target[44][45]. This gives

$$\sigma_{b\bar{b}} \approx 60\mu\mathrm{b},$$

producing $2.6 \times 10^{10}$ events per year at $10^7$ interactions per second. The solid angle required is much smaller, and the particles naturally hit the vertex detector at nearly normal incidence, so the detector is considerably simplified. Two Expressions of Interest were submitted to the SSC, one proposing to use crystal channeling to extract the beam and the other proposing to use a gas jet target. While the number of $B$'s produced is smaller than for the collider mode, it is still much greater than any $e^+e^-$ $B$-factory under discussion and sufficient to study CP violation. Thus, these proposals deserve more study.

## XI. LOW $p_T$ PHYSICS

While low-$p_T$ physics is not currently fashionable, it does represent the other 99% of the cross section, and it the forms the basis for our understanding of jet fragmentation and hence for many results on hard scattering. At SSC energies, the inclusive cross section for jets is comparable to the total cross section, so perturbative QCD plays a role in strong interactions. Furthermore, one can study the jet-jet cross section in the limit $\hat{s} \gg p_T^2$, where $\hat{s}$ is the square of the jet-jet center-of-mass energy. This cross section is controlled by a "Pomeron" which is calculable in the framework of perturbation theory by summing a suitable set of ladder graphs[46]. The calculation looks a lot like the old multiperipheral model, but because the jets are in the perturbative regime, it is actually a justified approximation to the underlying field theory. By comparing the behavior of jet cross sections for $\hat{s} \gg p_T^2$ with that of the total cross section, one can hope to gain new insight into strong interaction dynamics.

Experiments to measure low-$p_T$ physics interact more with the accelerator than typical high-$p_T$ experiments and so must be designed early even though the experiments themselves are relatively small. Considerable effort was made at this workshop to design a high-$\beta$ insertion region suitable for measuring the total cross section, the elastic cross section, and other low-$p_T$ phenomena.

## XII. SPECIALIZED DETECTORS

Since new particles are typically produced with $p_T \lesssim m$ and decay into several quanta, kinematics dictates that any detector aimed at searching for new particles must cover a large solid angle. For $m \sim 1\,\mathrm{TeV}$ at the SSC, covering $\eta \lesssim 2.5$ for jets, leptons, and photons; measurements of missing $p_T$ require hadronic coverage extending to $\eta \lesssim 5.5$. Thus it is unlikely that there will be any small detectors at the SSC capable of searching for new particles. It may, however, be possible to design detectors which offers significant advantages over the general-purpose ones for particular physics topics. Two such possibilities were discussed at this workshop: a high-luminosity detector and a dedicated $H \rightarrow \gamma\gamma$ detector.

*High-Luminosity Detector:* The SSC might eventually provide a luminosity at least ten times greater than the design value, $10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. At such luminosities, it is unclear that tracking is possible, and calorimetry will suffer from significant pileup, but it should be possible to search for some signatures. One specific suggestion, the Electron-Muon Detector ELMUD, has a fine-sampling electromagnetic calorimeter covering $\eta < 1.5$ with a resolution

$$\frac{\Delta E}{E} \approx \frac{7\%}{\sqrt{E}} \oplus 1\%$$

with a small scintillating-fiber tracker to find track stubs entering it. This is surrounded by absorber and an iron-toroid muon system covering $\eta < 2.5$. The calculations indicate that such a detector could cover a substantial range of physics, including $H \rightarrow \gamma\gamma$, $H \rightarrow Z^0 Z^0 \rightarrow 4\ell$, $W^\pm Z^0 \rightarrow 3\ell$ interactions, $Z' \rightarrow \ell\ell$, $\omega_{TC} \rightarrow Z^0\gamma \rightarrow \ell\ell\gamma$, and $\rho^\pm_{TC} \rightarrow W^\pm Z^0 \rightarrow 3\ell$.

It is important to realize that part of the gain from higher luminosity will be lost because of reduced acceptance and greater backgrounds. For example, ELMUD only covers electrons for $\eta < 1.5$, whereas the general-purpose detectors cover at least $\eta < 2.5$. If one only detects muons, as in the $10^{34}$ EoI, then one loses a factor of four in the observable rate for $H \rightarrow 4\ell$. The costs and benefits relative to upgrading a general-purpose detector for high luminosity deserves more study.

The other specialized detector discussed in the working groups was a dedicated $H \rightarrow \gamma\gamma$ detector. The proposal is to use $BaF_2$ with a highly segmented TMAE readout, giving good energy resolution,

$$\frac{\Delta E}{E} = \frac{4\%}{\sqrt{E}} + 0.5\%$$

plus information on the direction of the electromagnetic shower to determine the location of the vertex. Such a detector could detect the standard model Higgs for $100\,\mathrm{GeV} < m_H, 150\,\mathrm{GeV}$ in one SSC year with at least 6 standard deviations significance and could extend down to 80 GeV after several years.

## XIII. CONCLUSIONS

After five Snowmass meetings plus numerous other workshops, it is gratifying to see real detectors beginning to emerge. What physics these detectors may eventually discover is unknown, but there is every reason to hope that it will give us a better understanding of why the standard model works so well and what may lie beyond it.

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