Recognizing Superpartners at LEP

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Abstract

There is a class of supersymmetric models which is well-motivated by hints of evidence for SUSY and consistent with all existing data. It is important to study the predictions of these models. They are characterized by $\tilde{M}_{N_3} \gtrsim \tilde{M}_{C_1} \gtrsim \tilde{M}_\nu \gtrsim \tilde{M}_{N_1}$ (where $\tilde{N}_i$ and $\tilde{C}_i$ are neutralino and chargino mass eigenstates), $|\mu| \lesssim M_1 \lesssim M_2 \approx M_Z$, $\mu < 0$, and $\tan \beta$ near 1. Their LEP signatures are mostly unusual. Most produced superpartners are invisible! A good signature is two photons plus large missing energy. There are also excess events at large recoil mass in the single photon plus nothing channel. We list the main signatures for charginos, stops, etc., which are also likely to be unconventional. This class of models will be definitively tested at LEP194 with 100 pb$^{-1}$ per detector, and almost definitively tested at LEP184.
I. INTRODUCTION

How might superpartners be detected if they exist? They could be found in direct production at colliders as energy or luminosity is increased and a threshold is crossed in either. Observing them of course requires triggering on such events, and separating the signal from backgrounds. Or, their effects could be seen from one-loop contributions. Most possible deviations from the Standard Model, whether particle production or loop effects, could not be interpreted as signals of supersymmetry, since supersymmetric signals are strongly constrained as to which processes they can contribute to. For example, SUSY production events should have missing energy (assuming $R$-parity conservation), while deviations caused by loop effects should show up most strongly in processes such as $Z \to b\bar{b}$ and $b \to s\gamma$ (but not in $b$ quark asymmetries).

In the past couple of years some evidence of such effects has been reported [1]. Here we do not wish to describe this evidence or argue that it is, in fact, evidence for superparticles, but to observe that it can only be interpreted as such evidence and be consistent with all existing data if certain parameters lie in certain ranges. Therefore, it is appropriate to study the predictions of models with such parameters. We can summarize these ranges approximately by

$$|\mu| \lesssim M_1 \lesssim M_2 \approx M_Z \lesssim \tilde{M}_{\ell_L} < \tilde{M}_{\ell_R}, \quad \mu < 0,$$
$$1.2 \lesssim \tan \beta \lesssim 1.8,$$
$$\tilde{M}_{\ell_1} \approx \tilde{M}_{\ell_R} \sim M_Z.$$  \hfill (1)

We focus upon models satisfying the following mass hierarchy, which results for many combinations of the above inputs:

$$\tilde{M}_{N_3} \gtrsim \tilde{M}_{C_1} > \tilde{M}_\nu > \tilde{M}_{N_2} > \tilde{M}_{N_1},$$
$$45 \lesssim \tilde{M}_{N_1} \lesssim 65 \text{ GeV}.$$  \hfill (2)

Here $\tilde{M}_{N_i}$ and $\tilde{M}_{C_1}$ are the (unsigned) neutralino and chargino mass eigenvalues, $\tilde{M}_{\ell_L}$ and $\tilde{M}_{\ell_R}$ are the left and right charged slepton masses, $\tilde{M}_\nu$ is the sneutrino mass, $M_1$ and $M_2$
are the $U(1)$ and $SU(2)$ gaugino masses at the electroweak scale, $\mu$ is the coefficient of the $H_UH_D$ term in the superpotential at the electroweak scale, and $\tan \beta$ is the ratio of the Higgs vevs. We also take the right slepton mass $\tilde{M}_{\ell R}$ to be of order 125 GeV, but this choice only indirectly affects the LEP analysis. We further impose $\tilde{M}_{N_2} - \tilde{M}_{N_1} \gtrsim 20$ GeV, so that we qualitatively expect events such as $\ell^+\ell^-\gamma\gamma E_T$ at Fermilab [2]. The models discussed here do not depend on the light stop mass indicated in (1) for their interest. However, the relative size of $\tilde{M}_{t_1}$ and $\tilde{M}_{C_1}$ affects the signatures considerably, so we examine all cases. We use the word “models” to denote different choices of the above parameters, all constrained to be in the ranges specified by (1) and (2). Our entire analysis is in terms of an effective general lagrangian at the weak scale, including soft supersymmetry breaking parameters.

The scenario defined by (1) is at present a well-motivated one to study for its implications for signals at LEP (and Fermilab), and that is the purpose of this paper. Further, the detectable signatures for LEP are rather non-standard. For example, the largest SUSY signals may occur as events with two photons and large missing energy, an excess of single photon events with recoil mass above about 140 GeV, an excess of events with two soft charged leptons and large missing energy, etc. Even though some superpartner production cross sections are large (of order 1 picobarn), giving hundreds of produced events, most are simply invisible! The signals that have been most often studied from charginos and neutralinos are relatively small in this scenario. The key features which give these models their unique character are large branching ratios to invisible final states of the sneutrinos and $\tilde{N}_3$, as well as a significant branching ratio for the radiative decay of $\tilde{N}_2$. In the following we first summarize the masses and decays predicted for individual superpartners, and then describe the resulting cross sections and signatures.

II. SPARTICLE PROPERTIES

Table [1] summarizes the properties of the relevant superpartners. The constraints in Eq. (1) imply [3] that $\tilde{N}_1$ is dominantly higgsino (the approximately symmetric combination
of $H_U$ and $H_D$), $\tilde{N}_2$ is mainly photino, and $\tilde{N}_3$ is mostly antisymmetric higgsino, but with a non-negligible zino component. The charginos are neither pure wino nor pure charged higgsino (The $U$ mixing matrix is approximately off-diagonal, while all of the $V$ mixing matrix elements are roughly the same magnitude). All of the results of Table I follow straightforwardly. We have included a row for the stop since it is motivated if there are deviations from the Standard Model in $R_b$ and $B(b \to s\gamma)$ \cite{1}, by electroweak baryogenesis \cite{4}, and to some observers by aspects of Fermilab data \cite{5,6}. However, the crucial features of the class of models we are studying do not change if we take the stop mass to be heavier than indicated in Table I.

As described in detail in Ref. \cite{7}, an important feature of the SUSY parameters chosen in (1) is a large value of $B(\tilde{N}_2 \to \tilde{N}_1\gamma)$. Consequently, photons will play a significant role in the signals within this class of models. The remainder of the $\tilde{N}_2$ decay rate is to 3-body final states. Of the possible 3-body decays, $\tilde{N}_2 \to \tilde{N}_1\ell^+\ell^-$ has the largest branching ratio, because of the relatively low slepton masses.

A key result of the mass hierarchy (2) concerns the sneutrino decay modes. The only two-body modes open are $\tilde{\nu} \to \tilde{N}_1\nu$ and $\tilde{\nu} \to \tilde{N}_2\nu$. In fact, the decay to $\tilde{N}_1\nu$ dominates, rendering the sneutrino almost entirely invisible. Likewise, since $\tilde{N}_3 \to \tilde{\nu}\nu$ dominates, $\tilde{N}_3$ is also mainly invisible. Since $e^+e^- \to \tilde{\nu}\tilde{\nu}$ and $e^+e^- \to \tilde{N}_1\tilde{N}_3$ are among the largest cross sections, most sparticle production at LEP is invisible. When $\tilde{\nu}$ or $\tilde{N}_3$ do have a visible decay, it contains a single $\gamma$, or possibly $\tilde{N}_3 \to \tilde{c}_L\tilde{c}_R \to \tilde{N}_2\ell^+\ell^- \to \tilde{N}_1\gamma\ell^+\ell^-$. 

The heaviest neutralino, $\tilde{N}_4$, has decays which are very similar to $\tilde{N}_3$. The dominant $\tilde{N}_4$ decay mode is $\tilde{\nu}\nu$. Up to a quarter of the total $\tilde{N}_4$ decay rate is to $\tilde{c}_L\ell$. So while most $\tilde{N}_4$’s are invisible, a significant fraction will produce $\ell^+\ell^-\gamma E$. If the Higgs mass is small enough and the $\tilde{N}_4$-$\tilde{N}_1$ mass splitting large enough, the decay $\tilde{N}_4 \to \tilde{N}_1h^0$ opens up, suggesting the possibility of a significant unconventional source of Higgs bosons at LEP. However, the amount of available phase space is small, limiting this branching ratio to at most a percent or two, rendering such prospects dim.
Charginos and stops decay very differently depending on their relative mass. Here we focus upon $\tilde{t}_1$ and $\tilde{C}_1$ since $\tilde{t}_2$ and $\tilde{C}_2$ are likely to be too massive to be important at LEP in the short term. There are three interesting possibilities: (i) $\tilde{M}_{C_1} > \tilde{M}_{t_1} + m_b$, (ii) $\tilde{M}_{t_1} > \tilde{M}_{C_1} + m_b$, and (iii) $\tilde{M}_{t_1} + m_b > \tilde{M}_{C_1} > \tilde{M}_{t_1} - m_b$. In region (i) the stop decays exclusively to $c\tilde{N}_1$, as no other two-body modes are kinematically allowed. For the chargino, both $\ell\tilde{\nu}$ and $\tilde{t}_1 b$ final states are allowed. Generically we expect both modes to have sizeable branching ratios, although phase space suppression or the size of the stop mixing angle can cause one or the other of the two modes to dominate. In region (ii) the decay $\tilde{t}_1 \to \tilde{C}_1 b$ accounts for virtually 100% of the rate, while $\tilde{C}_1 \to \ell\tilde{\nu}$ dominates the chargino decays, so that stops mainly end up as a $b\ell\tilde{\nu}$ ($= b\ell+\text{invisible}$) final state. In some cases, $\mathcal{B}(\tilde{C}_1 \to W^*\tilde{N}_1)$ can be significant (i.e. a few percent), though seldom dominant. This is because we exclude the small corner of parameter space where $\tilde{M}_{C_1} \approx \tilde{M}_{\nu}$, since constraints from LEP161 and LEP172 suggest that $\mathcal{B}(\tilde{C}_1 \to W^*\tilde{N}_1)$ is probably small for $\tilde{C}_1$. Region (iii) combines features from the first two regions: we have $\mathcal{B}(\tilde{t}_1 \to \tilde{N}_1 c) = 100\%$ (as in region (i)), but the $\tilde{C}_1$ decays mostly to $\ell\tilde{\nu}$, (as in region (ii)). In the cases where the dominant $\tilde{C}_1$ decay is to $\ell\tilde{\nu}$, we note that most reported limits on $\tilde{M}_{C_1}$ do not apply, both because the $\tilde{C}_1$ decay is non-standard and because the $\tilde{C}_1$ cross section is reduced by $\tilde{\nu}$ exchange for our range of $\tilde{M}_{\nu}$.

### III. LEP CROSS SECTIONS AND SIGNATURES

We discuss those signals which are large enough to be detectable at LEP with $\sim 100$ pb$^{-1}$ per detector at a center of mass energy $\sqrt{s} = 184$ GeV. The cross section estimates presented below were obtained using the SPYTHIA Monte Carlo [8,9].

Although $\tilde{N}_1\tilde{N}_3$ and $\tilde{\nu}\tilde{\nu}$ production are among the largest cross sections, they are almost entirely invisible, as described above. However, on occasion we have $\tilde{\nu} \to \tilde{N}_2(\to \tilde{N}_1\gamma)\nu$, implying $e^+e^- \to \tilde{\nu}\tilde{\nu} \to \gamma I$, where we use $I$ to stand for a set of invisible particles. Since $I$ includes two $\tilde{N}_1$’s and a neutrino, and one of the $\tilde{N}_1$’s must combine with the neutrino to form an on-shell sneutrino, the minimum missing invariant mass is $\tilde{M}_{\nu} + \tilde{M}_{N_1} \approx 120$ GeV.
Similarly, on occasion $\tilde{N}_1\tilde{N}_3$ will give rise to $\tilde{N}_1\tilde{\nu}(\rightarrow \tilde{N}_1\gamma\nu)\tilde{\nu}$, with a missing invariant mass of at least $2\tilde{M}_{N_1}$. The production of $\tilde{N}_2\tilde{N}_3$ followed by the dominant $\tilde{N}_2$ and $\tilde{N}_3$ decays also leads to a single photon plus missing energy: in fact, this mode accounts for the majority of the $\gamma I$ total rate. Photons can also be radiated from the initial electrons (or from the $t$-channel chargino in $\tilde{\nu}\tilde{\nu}$ production, although this contribution is small); the threshold recoil mass here for $\tilde{\nu}\tilde{\nu}$ is about 150 GeV, and for $\tilde{N}_1\tilde{N}_3$ about 120 GeV. Other channels that can give a photon include $e^+e^-\rightarrow \tilde{N}_1\tilde{N}_1$ with a radiated $\gamma$, $e^+e^-\rightarrow \tilde{N}_1\tilde{N}_2(\rightarrow \tilde{N}_1\gamma)$, etc., but these give a smaller contribution [10]. The entire effect can be large, giving an excess over the Standard Model single photon rate for large missing invariant mass as one signature for supersymmetry. In the models we are considering, the total SUSY-related $\gamma I$ rate is typically between 100 and 300 fb. Once the signal is detected, it constrains the $\tilde{N}_1$, $\tilde{N}_2$, $\tilde{N}_3$, and $\tilde{\nu}$ masses.

Of course, there is a background for this $\gamma I$ channel from $\gamma Z(\rightarrow \nu\bar{\nu})$ and direct $\gamma\nu\bar{\nu}$ production via $W$-exchange. Most of the background is not in the region of interest here (missing mass well above $M_Z$), but enough is that some study is required to determine the best cuts on the observed photon. The authors of Ref. [11] have studied largely invisible SUSY signatures and how they might appear in the $\gamma I$ channel. The SUSY cases they examine do not overlap ours, but some of the phenomenology is the same. Their comments on Standard Model backgrounds are relevant, particularly for $e^+e^-\gamma$ events where neither lepton is detected.

Another channel that can give a signal is:

$$e^+e^-\rightarrow \tilde{N}_2\tilde{N}_2 \rightarrow \gamma\gamma I.$$ (3)

This channel is particularly interesting because about six events with missing invariant masses greater than 100 GeV have been reported [12] from LEP161 and LEP172 running.

1 $\tilde{N}_2\tilde{N}_3$ production followed by $\tilde{N}_2 \rightarrow \tilde{N}_1\gamma$ and $\tilde{N}_3 \rightarrow \gamma\tilde{N}_1\nu\bar{\nu}$ provides another (but much smaller) source of $\gamma\gamma I$ events.
combining all four detectors and both energies. The events are precisely in the region where we expect a signal in our models (\(i.e.\) missing invariant mass above 100 GeV).

It is very important to know the Standard Model background well, since the signal may only be a few times larger. The best estimate of the background is by S. Ambrosanio [13], who has done a careful calculation at tree-level using \texttt{CompHEP3.0} [14]. For photons satisfying the requirements \(E_\gamma > 8\) GeV, \(|\cos \theta_\gamma| < 0.95\), and \(\mathcal{M} > M_Z + 4\Gamma_Z\), he finds a cross section of \(20 \pm 2\) fb, which gives a background of 1.6 events for perfect photon detection efficiency. Assuming an average photon efficiency of 0.8, the final expected background is about 1.3 events. We have made checks using \texttt{PYTHIA} [8] (which is not ideal for such calculations), and find numbers consistent with Ambrosanio’s, and certainly not noticeably larger. If a signal is found, a precise evaluation of the higher-order corrections to this background would be useful. As far as we know, this has not yet been carried out.

The signal has a missing invariant mass \(\mathcal{M}\) larger than \(2\tilde{M}_{N_1}\), and photons that are never very soft (because we require \(\tilde{M}_{N_2} - \tilde{M}_{N_1} > 20\) GeV). The energy range for the photons produced in (3) is

\[
E_{\text{min,max}} = \frac{\sqrt{s}}{4\tilde{M}_{N_2}^2} (\tilde{M}_{N_2}^2 - \tilde{M}_{N_1}^2) \left(1 \mp \sqrt{1 - 4\tilde{M}_{N_2}^2/s}\right)
\]

(4)

where \(\tilde{M}_{N_1}\) and \(\tilde{M}_{N_2}\) are the neutralino masses and \(\sqrt{s}\) is the beam energy. Although initial state radiation and detector resolution effects will result in some photons having less energy than this minimum, the majority of the signal events in our models will have \(E_\gamma > 8\) GeV. In contrast, the background (from \(\gamma\gamma Z(\rightarrow \nu\bar{\nu})\) and \(\gamma\gamma\nu\bar{\nu}\)) has a missing invariant mass distribution which is concentrated around the \(Z\) peak; those background events which do have large \(\mathcal{M}\) tend to contain low-energy photons. Thus, the analysis should impose a minimum energy requirement of about 8 GeV for each photon, and define three regions for \(\mathcal{M}\), say \(\mathcal{M} < M_Z - 10\) GeV, \(M_Z - 10\) GeV < \(\mathcal{M} < M_Z + 10\) GeV, and \(\mathcal{M} > M_Z + 10\) GeV.

The signal we predict is entirely in the region \(\mathcal{M} > M_Z + 10\) GeV, while little background is in this region (see above). Of course, if softer photons or events from the \(Z\) peak are included in the signal region it will be harder to detect a signal. Even with our tightly
constrained parameter space there is a large variation in $\sigma(\gamma\gamma I)$, but the majority of the parameter space gives cross sections at LEP184 from 50–400 fb. (If we consider only those models which imply 3–10 events of $\gamma\gamma I$ at LEP161+LEP172, then this range narrows to 100–220 fb.) Note that this channel is independent of the single photon channel as a SUSY signal. Once the signal is detected, it constrains the $\tilde{N}_1$ and $\tilde{N}_2$ masses.

If the value of $\mathcal{B}(\tilde{N}_2 \to \tilde{N}_1\gamma)$ is only somewhat larger than 50%, the process $e^+e^- \to \tilde{N}_2\tilde{N}_2 \to \ell^+\ell^-\tilde{N}_1\tilde{N}_1\gamma$ can become important. The signal in this case is large missing energy ($E > 2\tilde{M}_{N_1}$) and two leptons with a pair mass many widths below the $Z$ ($M_{\ell\ell}^2 \lesssim \tilde{M}_{N_2}^2 - \tilde{M}_{N_1}^2$).

Our parameter space contains models with up to 200 fb in this channel.

The other channels at LEP184 which could have sizeable cross sections are $\tilde{C}_1^+\tilde{C}_1^-$ and $\tilde{t}_1\tilde{t}_1$ (see Fig. [a]). For charginos, we just combine the single chargino results above. In region (i), chargino decays to $\tilde{t}_1b$ and $\ell\tilde{\nu}$ can be comparable, so there are three different signatures: $\ell^+\ell^-E (E > 2\tilde{M}_\nu)$, $bc\bar{c}E (E > 2\tilde{M}_{N_1})$, and $\ell^\pm bcE (E > \tilde{M}_{N_1} + \tilde{M}_\nu)$. Here and below $\ell$ and $\ell'$ are any charged leptons, but $\ell'$ can be different from $\ell$. In regions (ii) and (iii), the decay $\tilde{C}_1 \to \ell\tilde{\nu}$ dominates, so chargino pairs primarily give $\ell^+\ell^-E (E > 2\tilde{M}_\nu)$. Because we have $\tilde{M}_{C_1} > \tilde{M}_\nu$, the decay $\tilde{C}_1 \to W^*\tilde{N}_1$ never dominates. However, it can lead to $\ell j j E (E > \tilde{M}_{C_1} + \tilde{M}_{N_1})$ as an additional signature, but at a much reduced rate. In all cases, $\ell^+\ell^-E (E > 2\tilde{M}_\nu)$ will be important as the chargino pair signature, with all combinations of $\ell = e, \mu, \tau$ and $\ell' = e, \mu, \tau$ possible. Since $\tilde{\nu}_e, \tilde{\nu}_\mu$, and $\tilde{\nu}_\tau$ are not guaranteed to be exactly degenerate, the relative number of each type of lepton pairs cannot be precisely predicted. Once such events are seen, they will provide information about the sneutrino mass splittings.

For stops we proceed similarly. In regions (i) and (iii) stop pairs produce $c\bar{c}E (E > 2\tilde{M}_{N_1})$. In region (ii) stop pairs give the signature $\ell^+\ell^-b\bar{b}E (E > 2\tilde{M}_\nu)$. Note that the $b$ and $\bar{b}$ can be very soft.

$^2\tilde{N}_1\tilde{N}_4$ production also provides a source of $\ell^+\ell^-\gamma E$ events (with differing kinematics). However, at LEP184 the cross section times branching ratio for this mode is at most about 10 fb.
The observation of $\ell^+\ell^-E \ (E > 2\tilde{M}_\nu)$ could signal either charginos or stops. The presence of a soft $bb$ pair, which might simply appear as a large hadron multiplicity, would tell us that $\tilde{M}_{t_1} > \tilde{M}_{C_1}$.

The biggest potential background to the $\ell^+\ell^-E$ channel is $e^+e^- \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}_\ell$. However, leptons coming from $W$-pair production are fairly stiff ($E_{\text{min}}^\ell \approx 24$ GeV at $\sqrt{s} = 184$ GeV)\(^3\) On the other hand, the $\tilde{C}_1-\tilde{\nu}$ mass difference in our models tends to be smaller than 10 GeV, and is frequently only a few GeV. Consequently, the maximum lepton energy coming from $\tilde{C}_1$ decay in $\tilde{C}_1^+\tilde{C}_1^-$ events at LEP184 is only a few GeV. Thus, a good event selection strategy would veto energetic leptons, but retain leptons which are as soft as possible.

Finally, in some of our models, left-handed slepton pairs are (barely) light enough to be produced at LEP184, giving $\ell^+\ell^-\gamma\gamma \ (E > 2\tilde{M}_{N_1})$. Unfortunately, the cross section is phase-space limited, and amounts to only 2–3 fb per slepton flavor.

**IV. FERMILAB**

In the scenario described in this paper, many light superpartners are produced at Fermilab. However, the combination of the near invisibility of $\tilde{N}_3$, $\tilde{N}_4$, and $\tilde{\nu}$ with the backgrounds at the Tevatron makes for few good signals. The sparticles which give potentially visible decays are the charginos (especially $\tilde{C}_2$), $\tilde{N}_2$, and the lighter stop (and, possibly, the gluino and heavier squarks: see the end of this section). At this point, some model dependence enters the discussion, as the relative masses of the $\tilde{C}_2$ and $\tilde{t}_1$ are important in determining their decay modes. However, two signals which are likely to be important are the inclusive $\gamma\gammaE_T + X$ and $\gamma bE_T + X$ rates. The first of these two signals is of interest in a wider category of models than considered here [13], while the second is special in that it has no significant

\(^3\) WW events containing two leptonic tau decays produce leptons which are much softer. However, this mode is suppressed by the branching ratio factor $[B(W \rightarrow \tau\nu)B(\tau \rightarrow \ell\nu\bar{\nu})]^2 = 1.5 \times 10^{-3}$. 

9
parton-level Standard Model background.

We begin our discussion with $\gamma\gamma E_T + X$. Both the Collider Detector at Fermilab (CDF) and D-Zero (D0) collaborations have reported results on searches for such a signal [16,17]. The CDF results are still preliminary, and do not yet include an upper limit on the $\gamma\gamma E_T + X$ rate. D0, however, reports the 95% C.L. upper limit

$$\sigma \cdot B(\bar{p}p \rightarrow \gamma\gamma E_T + X) < 185 \text{ fb}$$

for photons satisfying the following cuts: transverse energy $E_T^\gamma > 12 \text{ GeV}$, pseudorapidity $|\eta^\gamma| < 1.1$, and missing transverse energy $E_T^\text{miss} > 25 \text{ GeV}$. Within the group of models we are studying here, we obtain this signal from $\tilde{C}_2^+ \tilde{C}_2^-, \tilde{C}_2^+ \tilde{N}_2, \tilde{N}_2 \tilde{N}_2, \tilde{\ell}_L^+ \tilde{\ell}_L^-$, and $\tilde{\ell}_R^+ \tilde{\ell}_R^-$ production. Since the production cross section for $\tilde{C}_2$ pairs at the Tevatron is large ($\sim 300–700 \text{ fb}$ in our models), it potentially provides the largest contribution to the signal. First, let us assume that the stop is heavy ($\tilde{M}_{t_1} > \tilde{M}_{C_2}$). Then, $B(\tilde{C}_2 \rightarrow \tilde{\ell}_L \nu) \sim \frac{1}{2}$, and, including the remaining branching ratios, we obtain a contribution of around 100 fb. However, when we account for the effects of the cuts employed by D0, we find that the total $\gamma\gamma E_T + X$ rate is never more than 60 fb, even when the other initial states are added. Thus, our models are consistent with current Fermilab search limits.

The expected number of $\gamma\gamma E_T + X$ events actually decreases if the stop mass is lowered. First, a smaller stop mass implies a smaller $\tilde{N}_2 \rightarrow \tilde{N}_1 \gamma$ branching ratio [4]. Second, if $\tilde{M}_{t_1} < \tilde{M}_{C_2}$, then the decay $\tilde{C}_2 \rightarrow \tilde{t}_1 b$ opens up, allowing for a $\gamma b E_T + X$ final state when the two charginos decay differently. This possibility is especially interesting since there is no significant parton-level source of such events within the Standard Model. Depending upon the value of $B(\tilde{C}_2 \rightarrow \tilde{t}_1 b)$, we estimate that the size of the $\gamma b E_T + X$ signal from $\tilde{C}_2^+ \tilde{C}_2^-$ could be up to 100 fb.

If $\tilde{M}_{t_1}$ is even somewhat lighter still, the decay $t \rightarrow \tilde{N}_2 \tilde{t}_1$ becomes allowed. In this case, $t\bar{t}$ production followed by $t \rightarrow \tilde{N}_2(\rightarrow \tilde{N}_1 \gamma)$ and $\bar{t} \rightarrow W^- b$ provides an additional source of $\gamma b E_T + X$ events. Although $B(t \rightarrow \tilde{N}_2 \tilde{t}_1)$ tends to be only a few percent at most, the $t\bar{t}$ production cross section is enormous ($\sim 7 \text{ pb}$). Thus, even a modest 1% value for this branching ratio can lead to an additional 100 fb of $\gamma b E_T + X$ production. In connection with this possibility, we note that if $t \rightarrow \tilde{N}_2 \tilde{t}_1$ is allowed, then it is likely (but not certain) that
\( \tilde{M}_{t_1} < \tilde{M}_{C_1} + m_b \), in which case the signal becomes \( \gamma b c \slashed{E}_T + X \). Additional consequences for the Tevatron which arise in models which allow top-to-stop decays are discussed in Refs. [5,6].

Finally, we remark that if charginos and sleptons are in the mass ranges of Table I, then in many models gluinos and squarks of the first two families fall in the mass range 200–300 GeV. These have large cross sections at Fermilab and might also be observable [3], possibly even in the present data sample. The signatures of some such events could cause them to be included in the top quark sample.

V. COMMENTS

This paper reports the predictions for LEP of a particular, interesting, region of the SUSY parameter space. It is worth reporting these predictions because they are quite different from those of most SUSY analyses. For example, the largest cross sections (\( \tilde{N}_1 \tilde{N}_3 \) and \( \tilde{\nu} \tilde{\nu} \)) are almost completely invisible; they only show up occasionally as a single photon plus large missing energy. The cleanest SUSY signature may be \( \gamma \gamma \) plus large missing energy, from \( \tilde{N}_2 \tilde{N}_2 \rightarrow \tilde{N}_1 \tilde{N}_1 \gamma \gamma \). Chargino pairs mainly give \( \ell^\pm \ell'^\mp \) plus large missing energy, where \( \ell \) and \( \ell' \) can be different leptons and are soft. Stop pairs and selectron pairs are also possible. If no signals are observed at LEP184, this SUSY scenario is almost, but not quite, eliminated. At LEP194, this scenario is completely excluded if no signatures are seen with \( \sim 100 \text{ pb}^{-1} \) per detector. Note that most, but not all, sets of masses consistent with Eqs. (1) and (2) are also consistent with all present data. This is because if (1) and (2) do indeed describe the real world, then the sparticles are on the verge of being detected.

If such signals are seen, it will be easy (and fun) to extract from even limited data the remaining parameters of the chargino, neutralino and left-handed slepton sectors, tan \( \beta \), and (if present) light stop to good accuracy, even in the most general framework of a softly

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4The interpretation of the large missing mass \( \gamma \gamma \slashed{E} \) events from LEP161 and LEP172 running as \( \tilde{N}_2 \tilde{N}_2 \) production would become untenable in the absence of a signal at LEP184.
broken supersymmetric theory. If a model such as those examined here was indeed observed, the implications for the structure of the fundamental theory will be unusually interesting, since some features are likely to be different from those in most minimal SUSY models. For example, $M_1/M_2$ seems to be nearer to unity than to $\frac{2}{3}\tan^2 \theta_W$, and $\tilde{M}_{\ell_L} < \tilde{M}_{\ell_R}$ (which could happen, for example, from the $D$-terms coming from an extra $U(1)$) If these signals are seen it is very likely that the lightest SUSY Higgs boson is accessible at LEP, and it is certainly detectable at Fermilab within a few years.

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FIG. 1. Estimated total production cross sections for stops and charginos at LEP \((\sqrt{s} = 184 \text{ GeV})\) as a function of their mass. For charginos, the cross section is rather dependent on the details of the model, so we indicate a range of values. Models with very light \((\lesssim 72 \text{ GeV})\) charginos that satisfy the constraints described in this paper are very difficult to construct.
TABLE I. Masses and main decays of sparticles relevant to LEP, for models satisfying the mass hierarchy of Eq. (2). Unless specific quark or lepton flavors are indicated, we quote the sum over all flavors.

| Mass (GeV) | Main Decays Mode(s) | Main Decays Fraction | Other Significant Decays Mode(s) | Other Significant Decays Fraction |
|------------|---------------------|----------------------|----------------------------------|----------------------------------|
| $\tilde{N}_1$ | 45–65 | stable | —— | —— | —— |
| $\tilde{N}_2$ | 65–85 | $\tilde{N}_1\gamma$ | 50–85% | $\tilde{N}_1\ell^+\ell^-$, $\tilde{N}_1q\bar{q}$ | each $\lesssim 25\%$ |
| $\tilde{N}_3$ | 90–110 | $\tilde{\nu}\nu$ | $\gtrsim 93\%$ | $\tilde{\ell}_L^\pm\ell^\mp$ | $\lesssim 7\%$ |
| $\tilde{N}_4$ | 115–140 | $\tilde{\nu}\nu$ | 75%–85% | $\tilde{\ell}_L^\pm\ell^\mp$ | $\lesssim 25\%$ |
| $\tilde{C}_1$ | 75–95 | $\tilde{\nu}\ell^a$, $\tilde{\nu}\ell$, $\tilde{\ell}_1^b$ | $\gtrsim 90\%$ | $\tilde{N}_1\nu$, $\tilde{N}_1q\bar{q}'$ | $\lesssim 10\%$ |
| $\tilde{C}_2$ | 110–140 | $\tilde{\nu}\ell^a$, $\tilde{\ell}_L\nu^d$, $\tilde{\ell}_1^b$ | $\gtrsim 95\%$ | $\tilde{N}_1\nu$, $\tilde{N}_1q\bar{q}'$ | $\lesssim 5\%$ |
| $\tilde{\nu}$ | 75–90 | $\tilde{N}_1\nu$ | $\gtrsim 98\%$ | $\tilde{N}_2\nu$ | $\lesssim 2\%$ |
| $\tilde{\ell}_L$ | 90–105 | $\tilde{N}_2\ell$ | $\gtrsim 94\%$ | $\tilde{N}_1\ell$ | $\lesssim 6\%$ |
| $\tilde{t}_1$ | 65–115 | $\tilde{N}_1c^h$, $\tilde{C}_1b^i$ | 100% | —— | —— |
| $h^0$ | 65–100 | $bb$ | $\sim 80\%$ | $\tau\bar{\tau}$ | $\sim 9\%$ |

*a* If $\tilde{M}_{C_1} < \tilde{M}_{t_1} + m_b$.

*b* If $\tilde{M}_{C_1} > \tilde{M}_{t_1} + m_b$.

*c* Phase space suppression of the 2-body decay modes can enlarge these 3-body modes.

*d* If $\tilde{M}_{C_2} < \tilde{M}_{t_1} + m_b$.

*e* If $\tilde{M}_{C_2} > \tilde{M}_{t_1} + m_b$.

*f* Violation of this bound requires careful tuning of the input parameters.

*g* The stop mass could be larger than 115 GeV without changing the essential features found in this class of models.

*h* If $\tilde{M}_{t_1} < \tilde{M}_{C_1} + m_b$.

*i* If $\tilde{M}_{t_1} > \tilde{M}_{C_1} + m_b$.

*j* This range is implied by the parameters examined in this paper but does not affect the essential features of the other sparticles in this class of models.