New Multi-Scale Supersymmetric Models with Flavor Changing Neutral Current Suppression

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Abstract

We discuss the phenomenology of a class of supersymmetric models in which some of the quark and lepton superfields are an integral part of a dynamical supersymmetry breaking sector. The corresponding squarks and sleptons are much heavier than any other superpartners, and could naturally have masses as high as \(~40\) TeV. We discuss a general set of conditions for acceptable flavor-changing neutral currents and natural electroweak symmetry breaking, and identify two particularly interesting new classes of theories. We discuss how phenomenological signatures of such multi-scale models at the CERN LEP II and Fermilab Tevatron colliders could significantly differ from previously considered scenarios. In particular, we give experimental signals which could be present if the left-handed selectron is much lighter than the right-handed one.

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A compelling solution to the gauge hierarchy problem is that the world is supersymmetric at short distances. Testing this hypothesis directly requires a discovery of the superpartners, which requires understanding their experimental signatures, which in turn depend on the supersymmetric spectrum. However we still lack a standard model of supersymmetry (SUSY) breaking, and a general phenomenological approach for SUSY breaking (SSB) introduces an extravagant number of free parameters. Thus, unless one has unambiguous data for physics beyond the standard model (SM), searches for SUSY inevitably involve numerous assumptions.

Even if all sparticles are out of near-term experimental reach, supersymmetrizing the SM can lead to observable effects such as lepton flavor violation (LFV), particle electric dipole moments (EDMs), and flavor-changing neutral currents (FCNCs). Many explanations for the non-observation of such effects appeared in the literature [1–10], and these also have the advantage of reducing the number of parameters needed to describe the superpartner masses and couplings. Clearly, given our lack of understanding of SSB, all schemes which account for the absence of flavor violation deserve serious study.

In general, the explanations which have been given previously fall into two classes.

1. **Approximate Global Symmetries** can constrain the SSB parameters. Suppression of FCNCs and LFV can arise either as a result of spontaneously broken horizontal flavor symmetries [9,10], or simply as a consequence of accidental approximate flavor symmetries of the SSB and mediation sectors [1, 2].

2. **Decoupling** of the first two generations of superpartners can suppress EDMs, FCNCs and LFV [3–8]. The sparticles which potentially mediate unacceptable flavor violation are those of the first two quark and lepton generations. The principle of naturalness (i.e., that fine-tuned cancellations between different terms should only occur as result of a symmetry) is usually used to argue that all superpartners should be lighter than \( \sim 1 \) TeV in order to explain the electroweak (EW) scale. However since the first two generations are only weakly coupled to the Higgs, the first two generations of scalars can naturally be much heavier without spoiling natural EW symmetry breaking (EWSB)\(^1\). Naturalness still requires the top squarks, the left-handed (L) bottom squark, the EW gauginos and the higgsinos to be lighter than \( \sim 1 \) TeV. Such a hierarchy in the superpartner spectrum could be a result of new gauge interactions which are carried by the first two generations and which are involved in dynamical SSB [6,7].

More generally, a hybrid of the above two solutions is possible. The FCNC constraints can be satisfied provided that, for the first two generations, the superfields with the same \( SU(3) \times SU(2) \times U(1) \) gauge quantum numbers either both strongly couple to SSB dynamics (so the scalar superpartners are very heavy) or both couple to the SSB sector weakly, but in an approximately flavor blind way. If, e.g., the L down type squarks are light and degenerate, and the right-handed (R) down type squarks are non-degenerate but very heavy, superpartner contributions to \( \Delta S = 2 \) and \( \epsilon_K \) are sufficiently suppressed.

Such a hybrid solution can be the result of dynamical SSB at relatively low energies (below \( \sim 10^{10} \) GeV) if some of the quarks and leptons superfields take part in the SSB dynamics. For example, in the model of Ref. [12], the hierarchical structure of quark and lepton masses is explained by making the “10’s” (of SU(5) [13]) composite, while the “\( \\bar{5}'s \)” are elementary. If the compositeness dynamics is also responsible for dynamical SSB [6,14], the composite squarks and sleptons will be much heavier than the other sparticles [6]. The fundamental superfields are only weakly coupled to the SSB sector. Since SUSY is most effectively communicated to the fundamental superpartners via \( SU(3) \times SU(2) \times U(1) \) gauge dynamics [1,2], the light sparticles with the same gauge quantum

\(^1\)If the SSB scale is too high, large logarithms can spoil natural EWSB [4], or give negative masses squared to the lighter squarks and sleptons [11].
numbers will be nearly degenerate. More generally, such a spectrum could result in any model with gauge-mediated SSB (GMSB) and new horizontal gauge interactions carried by some quarks and leptons, as well as the SSB sector.

This hybrid scenario can be even more effective at suppressing FCNCs in a natural way than the pure decoupling scenario, for two reasons. First, the strongest bound on flavor and CP violation in the SUSY parameters comes from the contribution of the “left-right” (L-R) operator $d_L s_d d_R s_L$ to $K\bar{K}$ mixing and $\epsilon_K$, and this is suppressed as long as either L or R down-type squarks are degenerate. Second, the naturalness upper bound of $\sim 20$ TeV on the superpartner masses assumes that all superpartners of the first two generations are heavy. Actually, the naturalness bound, which comes from two loop graphs involving SU(2) gauge fields, is on the average mass squared of SU(2) doublets. For example, the R $d$-squarks and L sleptons could naturally be as heavy as $\sim 40$ TeV, provided the other scalars are lighter.

Theories with non-universal scalar masses which are larger than $\sim 1$ TeV potentially generate a disastrous large Fayet-Iliopoulos (FI) term [15] for weak hypercharge [4]. The simplest way to avoid a FI term is an SU(5) approximate global symmetry of the SSB dynamics. Thus, we will assume that the heavy sparticles come in complete SU(5) multiplets with nearly degenerate masses.

With this SU(5) assumption, there are two classes of SSB theories which avoid FCNCs and FI terms, allow natural EWSB, and which have never been previously discussed. In the following, we will refer to such a theory as a Hybrid Multi-Scale Supersymmetric Model (HMSSM).

**HMSSM-I**: All the sparticles are lighter than $\sim 1$ TeV, except for the scalar superpartners of the first two generations which transform as 10’s (L squarks, R up and charm squarks, and R sleptons). The light sparticles with identical SU(3) $\times$ SU(2) $\times$ U(1) quantum numbers are assumed to be nearly degenerate.

**HMSSM-II**: All the sparticles are lighter than $\sim 1$ TeV, except for the scalar superpartners which transform as a 5’s (R down squarks and L sleptons). We further break this class down into HMSSM-IIa, where the R bottom squark and L $\tau$ and $\nu_\tau$ sleptons are heavy, and HMSSM-IIb, where the R bottom squark and L $\tau$ and $\nu_\tau$ sleptons are light. The light sparticles of the first two generations with identical SU(3) $\times$ SU(2) $\times$ U(1) quantum numbers are nearly degenerate.

The HMSSM-I and HMSSM-IIb are distinguished from the HMSSM-IIa by treating the third generation differently from the first two. As a consequence, there are potentially detectable new contributions to CP violation in $B$ decays [16] and lepton flavor violation, while such effects will be much smaller in the HMSSM-IIa.

In the following, we explore the effects of multiple scales for superpartner masses on SUSY searches at LEP II and Tevatron. A complete examination is beyond the scope of this letter, so we will just give a few illustrative examples of some possible dramatic effects, mainly within the HMSSM-I. We will assume the lightest superpartner (LSP) is the gravitino ($\tilde{G}$). However the fundamental SSB scale may be high enough ($\gtrsim 10^6$ GeV) so that decays into the $\tilde{G}$ do not occur inside the detector. Motivated by our assumption that the SUSY breaking masses for gauginos and first two generation light superpartners are mainly gauge mediated, we assume the conventional grand-unified relations amongst the gaugino masses and, for the light sparticles, a spectrum consistent with a general GMSB pattern, e.g. colored superpartners are substantially heavier than color neutral ones. The SUSY signatures depend dramatically on which sparticle(s) can decay dominantly to the $\tilde{G}$ (see, e.g., Ref. [17]). Often, this is only the case for the next-to-lightest superpartner (NLSP). With our assumptions, in the HMSSM-I, the NLSP is either a neutralino, or the lightest (most likely R) tau slepton $\tilde{\tau}_1$, or (one of) the sneutrinos. More complex (“co-NLSP”) scenarios with more than one sparticle decaying directly into the $\tilde{G}$ might occur as well. In the HMSSM-II, the (co-)NLSP can be a neutralino and/or the (R) $\tilde{\tau}_1$, or all the R sleptons could be co-NLSPs. Furthermore, for the HMSSM-IIb only, the tau sneutrino can play a (co-)NLSP role. In general,
for $\tan \beta$ not too large ($\lesssim 4$ to 20, depending on the model details), the lightest neutralino $\tilde{N}_1$ is usually the NLSP. For simplicity, we mainly consider this possibility. However, in all models, the $\tilde{\tau}_1$ is amongst the light sparticles, and with our assumptions, it is always one of the lightest scalars. Therefore, in any version of the HMSSM, a signal from $\tilde{\tau}_1\tilde{\tau}_1$ production is a prime candidate for discovery at LEP II. If $\tilde{\tau}_1$ is the NLSP, such a signal could feature energetic, central tau leptons and large $E_t$ or tracks from massive, long-lived charged particles, depending on whether the SSB scale is low ($\lesssim 10^5$ GeV) or much higher. However, such signatures can also arise from conventional GMSB models [17–19].

When $\tilde{N}_1$ is the NLSP, the model phenomenology and the existing bounds from experimental data crucially depend on whether the decay $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ occurs (i) promptly, (ii) (mostly) inside the detector, or (iii) outside, which in turn depends on the SSB scale. Case (i) is of special interest, leading to a variety of unusual events with $\gamma\gamma + X + E_t$ at colliders [18–25]. One of them, where $X = 2$ charged leptons, might have been observed at Fermilab by CDF [20, 26, 27]. In case (i) [(ii)], an inclusive search for events with two energetic, central [displaced] photons and $E_T$ in the present Tevatron data sample [28] can at least exclude masses for $\tilde{N}_1$ and the lightest chargino $\tilde{C}_1 \lesssim 70$ and 125 GeV, respectively, in a model independent way [22]. Thus, the only fermion sparticle production process within LEP II reach is NLSP pair production. A further consequence of the $\tilde{N}_1$ and $\tilde{C}_1$ mass lower limits is that, within the parameter space of interest for SUSY at LEP II ($m_{\tilde{N}_1} \lesssim 95$ GeV), they select a region where $\tilde{N}_1 \sim$ B-ino ($\tilde{B}$), which couples most strongly to the $\tilde{e}_R$. Also, the relations $m_{\tilde{C}_1} \sim m_{\tilde{N}_2} \sim 2m_{\tilde{N}_1}$ turn out to be always fulfilled. All these considerations must also apply to the HMSSM, since they only come from assumptions about the NLSP and the SSB scale, in addition to gaugino mass unification.

For example, consider the HMSSM-I where L slepton pairs can be produced in a future LEP II run, i.e. $m_{\tilde{e}_L}, m_{\tilde{\mu}_L} < 95$ GeV, while the R selectron $\tilde{e}_R$ is very heavy. We also assume that the $\tilde{N}_1$ is the NLSP, and that the $\tilde{N}_1$ decays into a photon and gravitino within the detector. Given a sufficient number of selectron events at LEP II, it is possible to use the total cross sections and forward-backward (F-B) asymmetry to deduce that the selectron events must be left-handed and therefore that the R selectron must be heavier.

In Fig. 1, we show the $\pm \cos \theta_{\ell z}^{\text{hard}}$ ($\ell = e, \mu$) distribution for $\tilde{e}_L\tilde{e}_L, \tilde{\mu}_L\tilde{\mu}_L$ production in two possible parameter sets for the HMSSM-I with $m_{\tilde{N}_1} \sim 75$ GeV, and $m_{\tilde{\nu}_1} = 85$ GeV. For comparison, analogous distributions are shown for the case of R slepton production, corresponding to two examples of conventional GMSB models with $\tilde{N}_1 = \text{NLSP}$ amongst those of Ref. [17]. The two sets of parameters chosen are compatible with all collider limits and, in the GMSB case, with EWSB conditions as well. Although the neutralino/chargino spectra and composition are similar, the parameters otherwise have little in common. Hence, the two choices can be thought as good examples of the general pattern. This polar angle parametrizes the F-B behavior of the charged leptons in the final state. It is important that the decay $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ occurs in the detector. The presence of hard, central (or displaced) photons eliminates the SM physics background and also allows the reconstruction of the $\tilde{N}_1$ and relevant selectron masses for each event. For the parameters chosen in Fig. 1, the final electrons (muons) have energies roughly in the range 5–15 GeV and can escape detection only when $|\cos \theta|$ is close to 1. For the smuons, the reactions can only proceed

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2 Actually, none of the methods given in this paper can distinguish between a moderately heavy selectron, $m_{\tilde{e}} \sim 300$ GeV, and the ultra heavy ($\gtrsim 5$ TeV) mass expected in a multi-scale model. Measurement of “super-oblique” parameters [29] could eventually further constrain the heavy selectron mass.

3 For the GSMB case, $\tilde{\ell}_R$ can be light, but $\tilde{\ell}_L$ pairs are always out of LEP II reach. Only in a small number of cases can $\tilde{e}_L\tilde{e}_R^\pm$ production be kinematically accessible.

4 Note that in the GMSB models of Ref. [17], if $\tan \beta \gtrsim 20$, then the $\tilde{\tau}_1$ is always lighter than the $\tilde{\ell}_R$ by $\gtrsim 10$ GeV. Thus, the model shown on the left side of Fig. 1 is a borderline $\tilde{N}_1 = \text{(co-})$NLSP case in conventional GMSB.
through s-channel $\gamma\gamma$ or $Z$-exchange, and the distributions and total cross sections are similar in the L and R cases. In contrast, for selectrons the cross section and degree of F-B asymmetry is very sensitive to the selectron handedness, due to the fact that $\tilde{e}_{L,R}\tilde{e}_{L,R}$ production also receives contributions from $t$-channel neutralino exchange. Amongst those, the light $\tilde{N}_1 \sim \tilde{B}$ and the heavier $\tilde{N}_2 \sim W^3$ dominate. In the $\tilde{e}_R\tilde{e}_R$ case, only the former contributes, giving rise to a 30–40% increase in the total cross section, when compared to smuon production. In addition, there is a clear preference for producing a final $e^-$ ($e^+$) in the same (opposite) hemisphere as the $e^-$ beam. In contrast, the combined contributions to $\tilde{e}_L\tilde{e}_L$ production not only produce destructive interference and a total cross-section reduction, but also the resulting F-B distribution is flatter. Still, in the two HMSSM-I cases of Fig. 1, in a 500 pb$^{-1}$ run at $\sqrt{s} = 190$ GeV each LEP detector should be able to observe 5–8 clean $e^+e^-\gamma\gamma + \not{E}_T$ events. One could then use the low cross section and smaller F-B asymmetry to ascribe such events to $\sim 85$ GeV $\tilde{e}_L\tilde{e}_L$ pair production while inferring that $\tilde{e}_R$ pair production is above threshold, in contrast to most other SUSY models. Such a method should work similarly for lighter selectrons, as long as the $\tilde{N}_1$ is the NLSP and heavier than 70 GeV and the selectron is at least a few GeV heavier still\(^5\). For selectrons heavier than $\sim 85$ GeV, lack of statistics will hinder the above strategy for HMSSM pattern recognition. However, as discussed below, $\gamma\gamma + \not{E}_T$ events from $\tilde{N}_1\tilde{N}_1$ production can provide another disentangling tool. Further, sneutrino production followed by $\tilde{\nu} \rightarrow \tilde{N}_1\nu$ must also occur in the HMSSM-I, while with GMSB it need not. Finally, in both the HMSSM-I and in GMSB models, one expects some $\tau^+\tau^-\gamma\gamma + \not{E}_T$ events from $\tilde{\tau}_1\tilde{\tau}_1$ production, since typically $m_{\tilde{N}_1} < m_{\tilde{\tau}_1} < m_{\tilde{e}_{L,R}}$.

For the case of degenerate L and R selectrons at 85 GeV, the two models considered in Fig. 1 would have a much higher selectron production cross section of 650–800 fb and a F-B asymmetry not too different from that of the $\tilde{e}_L\tilde{e}_L$ case. However, such degeneracy cannot be realized in either the HMSSM or GMSB frameworks.

We now consider the HMSSM-I in the case where all slepton production is above threshold at LEP II, while the $\tilde{N}_1$ is the NLSP and is within reach. We assume the $\tilde{N}_1$ decays into a photon and gravitino promptly\(^6\), so that $e^+e^- \rightarrow \tilde{N}_1\tilde{N}_1$ with signature $\gamma\gamma + \not{E}_T$ is the only observable SUSY signal. First of all, notice that the production cross section is always too small to allow significant occurrence of such events in the limited samples collected at LEP with c.m. energies $\sqrt{s} = 161–172$ GeV, irrespective of the particular model considered. This is in full agreement with the data on $\gamma\gamma + \not{E}_T$ events consistent with $\tilde{N}_1 \rightarrow \tilde{G}\gamma$ kinematics, with $m_{\tilde{N}_1} \gtrsim 70$ GeV [17, 22, 28]. However, the sensitivity of the $\tilde{N}_1\tilde{N}_1$ production process to large L-R mass hierarchies in the selectron sector can still distinguish the HMSSM-I from GMSB models in a rather clean way, provided that a good number of NLSP pairs are produced in the forthcoming high-luminosity LEP II run(s). As Fig. 2 shows, if $m_{\tilde{N}_1} \lesssim 85$ GeV, such production can occur, but is not guaranteed.

\(^5\)A similar disentangling technique would not be as effective in the case where selectrons, smuons and staus act as co-NLSPs and direct $\tilde{e}$, $\tilde{\mu}$ decays to $\tilde{G}$ are present, for two reasons. First, the lack of photons in the final state would make it harder to subtract the SM backgrounds, especially the one from $WW$. Unavoidably, severe cuts should be applied to the signal, with consequent loss of statistics. Second, the $B - W^3$ pattern in the light neutralino sector would not hold in a model independent way.

\(^6\)When the SSB scale is high enough so that the photon vertex is displaced, the near absence of SM background makes our arguments even stronger, while when the $\tilde{N}_1$ does not decay in the detector there is no visible signal.

\(^7\)Such cuts also avoid any possible contamination from events due to $\tilde{N}_2\tilde{N}_2$ production and subsequent double $\tilde{N}_2 \rightarrow \tilde{N}_1\gamma$ radiative decay in SUGRA(-like) models.
\(m_{\tilde{N}_1} = 80\) GeV, GMSB models with prompt \(\tilde{N}_1 \rightarrow \tilde{G}\gamma\) decay predict more than about 40 and up to 100 clean \(\gamma\gamma + E_T\) events, while the HMSSM-I cannot give more than about 10. The larger cross section in GMSB models is due to an effective upper bound on \(m_{\tilde{e}_R}\) for a given NLSP mass \([17]\) and the large contribution to \(\tilde{N}_1\) pair production from \(t\)-channel \(\tilde{e}_R\)-exchange. (The contribution from \(\tilde{e}_L\)-exchange is much smaller.) Note that a clean measurement of the \(\tilde{N}_1\) mass is possible by using the kinematics of the production followed by \(\tilde{N}_1 \rightarrow \gamma\tilde{G}\) decay, after a selection of the events with the highest photon energies. However, as \(m_{\tilde{N}_1}\) grows and the threshold for pair production approaches, in the HMSSM-I only a few \(\gamma\gamma + E_T\) events would be observed against a non-negligible background, so that such a discriminating method would be ambiguous. Also, one could be unlucky and observe at most a very scarce signal, even for \(m_{\tilde{N}_1} < 85\) GeV. On the other hand, detection of a relatively copious \(\gamma\gamma + E_T\) (or displaced-photon) signal, possibly for \(m_{\tilde{N}_1}\) as large as 90 GeV, would exclude the HMSSM-I. When \(\tilde{t}_L\) pair production is also allowed, the upper border of the hatched region rises somewhat \([cfr.\ grey\ (or\ blue)\ curve\ in\ Fig.\ 1]\) so that, \(e.g.\) for \(m_{\tilde{N}_1} = 80\) GeV, one can have up to about 12 events after cuts\(^8\). However, such a case is often realized when \(m_{\tilde{t}_L} \lesssim 85\) GeV and one has other signals and disentangling tools available. An intermediate, more involved case \((cfr.\ dashed\ line\ in\ Fig.\ 1)\) occurs when \(m_{\tilde{N}_1} < m_{\tilde{\nu}} < 95\) GeV \(< m_{\tilde{t}_L}\). Here, the presence of additional \(\gamma\gamma + E_T\) events from sneutrino production might give some background to the \(\tilde{N}_1\tilde{N}_1\) signal. However, it should be in principle possible to distinguish sneutrino-generated events from direct-neutralino production events, for instance by observing that the former generally feature softer photons and a larger missing energy. Also, when sneutrinos can be produced it is likely that stau-pair production also occurs. A final general observation is that photon angular distributions are not a very good discriminant, especially if the produced NLSPs are heavy, since the final state pattern is dominated by the kinematics of the \(\tilde{N}_1 \rightarrow \tilde{G}\gamma\) decay which is isotropic in the NLSP rest frame.

A completely different scenario arises if the NLSP does not decay inside the detector. Unlike the usual supergravity (SUGRA) case however, the gravitino is the LSP, and cosmological arguments do not require \(\tilde{N}_1\) to be the NLSP. If, \(e.g.\) the NLSP were \(\tilde{\tau}_1\), SUSY events would not contain missing energy but heavy charged tracks. If the NLSP were \(\tilde{N}_1\), then signatures of SUSY events would be somewhat similar to those of SUGRA models, but even in this case the unusual hierarchy of slepton masses could induce differences between the HMSSM-I and conventional SUGRA models in the sparticle production cross sections and in the branching fractions (BRs) for their decays. Unfortunately, when the \(\tilde{N}_1 = \text{NLSP}\) is nearly stable, the limits on the \(\tilde{N}_1\) and \(\tilde{C}_1\) masses are neither as general nor as stringent as in the unstable case. Therefore, various compositions and spectra are allowed for light \(\tilde{N}_{1,2}\) and \(\tilde{C}_1\), which makes it harder to find a clean discriminant.

On the other hand, with a nearly stable \(\tilde{N}_1 = \text{NLSP}\), heavier neutralino-pair production, as well as \(\tilde{C}_1^+\tilde{C}_1^-\) pair production, could occur at LEP II and provide a larger number of useful observables. Indeed, in most HMSSM-I scenarios, we find a significant reduction of the cross section for \(\tilde{N}_1\tilde{N}_2\) production at LEP II with respect to conventional SUGRA models. This process is especially sensitive to the right handed selectron mass when the lighter neutralinos are mostly gauginos. Also, perceivable differences in both the BRs and some final-state distributions are often present after the \(\tilde{N}_2\) decay into the \(\tilde{N}_1\). The angular distributions are especially affected when the decay process can be mediated by (on-shell) light L or R sleptons, as in the case \(\tilde{N}_2 \rightarrow \tilde{N}_1\ell^+\ell^-\). As an example, consider the fact that a drastic enhancement of the \(\tilde{N}_2\) visible leptonic BR can be realized in a SUGRA model with \(m_{\tilde{e}_R} \lesssim m_{\tilde{N}_2}\), while in the HMSSM-I this is much more difficult. Indeed, one has to force \(m_{\tilde{\nu}} < m_{\tilde{e}_L} \lesssim m_{\tilde{N}_2}\), which often gives rise to a substantial increase of the invisible

\(^8\)In the models considered in Fig. 2 with \(\tan\beta > 1.2\), this is only possible for \(m_{\tilde{N}_1} \lesssim 88.7\) GeV, otherwise the sneutrinos become lighter than the \(\tilde{N}_1\).
fraction as well. Although $\tilde{N}_1\tilde{N}_2$ searches allow exploration of a wider region of the gaugino-higgsino parameter space than chargino searches do, low cross sections and severe backgrounds could render very difficult a post-discovery disentangling analysis based only on neutralinos.

Signatures which use $\tilde{C}_1^+\tilde{C}_1^-$ production to distinguish the HMSSM-I from SUGRA models are difficult to find, since $\tilde{C}_1^+\tilde{C}_1^-$ production is insensitive to the R selectron mass. One might hope to use, e.g., a reduced hadronic chargino BR due to super-heavy L squarks as a signal for the HMSSM-I, but squarks are quite heavy in many other models as well. However, the HMSSM-II differs from SUGRA models in that $\tilde{C}_1^+\tilde{C}_1^-$ production only proceeds through s-channel $\gamma\gamma$ or $Z$-exchange, and, in contrast to SUGRA models, the contributions from t-channel $\tilde{t}$-exchange can never reduce the cross-section at LEP II. Chargino BRs are also of interest, since a very large leptonic fraction cannot be achieved in either version of the HMSSM-II, while such BRs could be large in either SUGRA or the HMSSM-I. Particularly interesting is the case of the HMSSM-IIb, where substantial lepton universality violation in chargino BRs and possibly in other quantities could be observed. If slepton production also occurs, then the prospects for HMSSM/non-HMSSM disentangling should be brighter, although SM-background reduction is still generally a more severe problem than when the decay $\tilde{N}_1 \to \tilde{C}\gamma$ is observed.

As for HMSSM phenomenology at the Tevatron, the unusual HMSSM L-R mass hierarchies are unlikely to generate striking signatures based on total cross-sections or distributions of SUSY production processes, given our hypothesis of relatively heavy squarks. However, some generic BR arguments can still be made. For instance, relative to SUGRA models, the HMSSM-I might give rise to an enhancement of the trilepton signal (when the NLSP is a nearly stable neutralino) while the HMSSM-II (especially HMSSM-IIa) would tend to give fewer trileptons.

One case where the HMSSM L-R slepton-mass hierarchy is important at Tevatron occurs if the famous $e^+e^-\gamma\gamma + E_T$ event reported by CDF [26] is a genuine SUSY discovery. Assuming the NLSP is the $\tilde{N}_1$ which decays promptly to $\tilde{G}\gamma$, the HMSSM-II (in particular HMSSM-IIa) cannot be compatible with the event and other limits from $\gamma\gamma + X + \not{E}_T$ inclusive searches unless the event comes from $\tilde{e}_R\tilde{e}_R$ production with $m_{\tilde{e}_R} \gtrsim 95$ GeV. However, the $\tilde{e}_R$ cannot be much heavier, since one already expects less than a single $e^+e^-\gamma\gamma + E_T$ event, before experimental cuts, for $m_{\tilde{e}_R} = 95$ GeV [20,27]. However, in the HMSSM-I it is possible to interpret the event either as $\tilde{e}_R\tilde{e}_L$ ($m_{\tilde{e}_L} \gtrsim 95$ GeV) production or as $\tilde{C}_1^+\tilde{C}_1^-$ production, followed by $\tilde{C}_1 \to \ell(\tilde{\nu}_\ell \to \nu_\ell\tilde{N}_1)$ [17,22,24]. (The latter provides twice as many events with differently flavored charged leptons.) Moreover, the $\tilde{N}_1$ mass is not correlated with the selectron masses as in conventional GMSB models [17,22,23,25]. Thus, the number of expected additional non-standard events can be reduced. In the chargino interpretation, models with $m_{\tilde{C}_1} - m_{\tilde{\nu}} > 20$ GeV, which seems preferred by the kinematics of the event, might be obtainable, whereas $m_{\tilde{C}_1} - m_{\tilde{\nu}} > 20$ GeV is incompatible with $\tilde{N}_1 = $ NLSP, e.g. in the large class of GMSB models analyzed in Ref. [17].

Thus, for instance, observation of a larger number of $\ell^+\ell^-\gamma\gamma + E_T$ events at the Fermilab Main Injector, combined with at most a small signal at LEP II from $\tilde{N}_1\tilde{N}_1 \to \gamma\gamma + \not{E}_T$, would be evidence for the HMSSM-I. For this scenario, there would probably be additional $\tau^+\tau^-\gamma\gamma$ events as well, especially at Fermilab, coming from $\tilde{\tau}_1$ production and decay.

In conclusion, we have considered general conditions under which theories with multiple scales for the soft supersymmetry breaking terms can avoid flavor changing neutral currents and large Fayet-Iliopoulos terms, while maintaining natural electroweak symmetry breaking. Such theories connect the two most mysterious aspects of supersymmetric models, namely the physics of flavor.

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9For a nearly-stable neutralino NLSP, an enhanced BR for the radiative $\tilde{N}_2 \to \tilde{N}_1\gamma$ decay is required to generate the photons. Then similar arguments apply to the HMSSM and conventional SUGRA models. In particular, this renders problematic a chargino interpretation compatible with other limits [20,27].
and of supersymmetry breaking. We have identified two new classes of models. These models have an unusual hierarchy in scalar superpartner masses, with either $m_{\tilde{e}_L} \ll m_{\tilde{e}_R}$, $m_{\tilde{q}_L} \sim m_{\tilde{u}_R} \gg m_{\tilde{d}_R}$ (the HMSSM-I), or $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$, $m_{\tilde{q}_L} \sim m_{\tilde{u}_R} \ll m_{\tilde{d}_R}$ (the HMSSM-II). As an example, we have shown in some detail how the slepton mass pattern $m_{\tilde{e}_L} \ll m_{\tilde{e}_R}$ can have distinctive experimental consequences.

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Figure 1: The $\pm \cos(\theta^\text{hard})$ distribution [fb] for various slepton-pair production processes at LEP II in two examples of conventional GMSB models of Ref. [17] (with $m_{\tilde{\ell}} = 85$ GeV and heavier $\tilde{\ell}_L$) and two possible parameter choices for the HMSSM-I (with $m_{\tilde{\ell}} = 85$ GeV and super-heavy $\tilde{\ell}_R$) where $m_{\tilde{N}} \simeq 75$ GeV. The polar angle refers to the most energetic final lepton $\ell = e$ or $\mu$ (after $\tilde{\ell} \to \tilde{N}_1 \ell$ decay), with respect to the $e^-$ beam direction. The + (-) sign is taken for the cosine if such lepton is positively (negatively) charged. The models considered are consistent with all collider limits (which in particular force $m_{\tilde{C}_1} > 125$ GeV), under the hypothesis that $\tilde{N}_1 = \text{NLSP}$ and the $\tilde{N}_1 \to \tilde{\ell} \gamma$ decays occur inside the detector. This plot has been obtained by explicitly generating 300K events for each process with SUSYGEN 2.17 [30]. Initial state radiation effects are included.
Figure 2: Total cross section [pb] for \( \tilde{N}_1 \tilde{N}_1 \) production at LEP II in all the conventional GMSB models of Ref. [17] (dark or blue region) and in HMSSM-I models (hatched region) with \( \tilde{N}_1 = \) NLSP and \( \tan \beta > 1.2 \). All the models are consistent with all collider limits (which in particular force \( m_{\tilde{C}_1} > 125 \text{ GeV} \)), under the hypothesis that the \( \tilde{N}_1 \rightarrow \tilde{G} \gamma \) decays occur inside the detector. The upper bound of the hatched region is given by the solid curve if \( m_{\tilde{\nu}} > 95 \text{ GeV} = [\sqrt{s}/2]_{\text{LEP II}} \); by the dashed one if \( m_{\tilde{\nu}_1} < m_{\tilde{\nu}} < 95 \text{ GeV} < m_{\tilde{e}_L} \); by the grey (or blue) one if both sneutrino and L selectron are below the threshold for pair production. Initial state radiation effects are included.