# Low-Energy Supersymmetry at Future Colliders

John F. Gunion

*Davis Institute for High Energy Physics,*
*Department of Physics,*
*University of California, Davis, CA 95616*

Howard E. Haber

*Santa Cruz Institute for Particle Physics,*
*University of California, Santa Cruz, CA 95064*

## Abstract

We classify the variety of low-energy supersymmetric signatures that can be probed at future colliders. We focus on phenomena associated with the minimal supersymmetric extension of the Standard Model. The structure of the supersymmetry-breaking introduces additional model assumptions. The approaches considered here are supergravity-mediated and gauge-mediated supersymmetry-breaking. Alternative phenomenologies arising in non-minimal and/or R-parity-violating approaches are also briefly examined.

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## 1 Introduction

In this chapter, we focus on the signatures for low-energy supersymmetry at future colliders in the context of the minimal supersymmetric extension of the Standard Model (MSSM) [1,2]. In its most general form (with the assumption of R-parity conservation), the MSSM is a 124-parameter theory [3,4]; most of the parameter freedom is associated with the supersymmetry-breaking sector of the model [a]. This huge parameter space can be reduced by: (i) imposing phenomenological constraints, and (ii) imposing theoretical assumptions on the structure of supersymmetry-breaking. In addition, the scale of supersymmetry-breaking, $\sqrt{F}$, must be specified. It determines the properties of the gravitino, $\widetilde{g}_{3/2}$. In previous chapters, two broad model categories for supersymmetry-breaking were discussed, gravity-mediated supersymmetry breaking (SUGRA) and gauge-mediated supersymmetry breaking (GMSB).

In most SUGRA models [5], $\sqrt{F}$ is so large that the $\widetilde{g}_{3/2}$ interactions are too weak for it to play any role in collider phenomenology. In the *minimal* supergravity (mSUGRA) framework, the soft-supersymmetry-breaking parameters at the Planck scale take a particularly simple form and depend on essentially five new parameters. These include $m_0$ (a flavor universal soft

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[a]The notation for the supersymmetric parameters used in this paper for the most part follows that of Ref. [2]. The notation for supersymmetric particle names follows that of Ref. [1].

supersymmetry-breaking scalar mass), $m_{1/2}$ (a universal gaugino mass), and $A_0$ (a flavor universal tri-linear scalar interaction). In particular, gaugino mass unification implies that at the unification scale $(M_X)$, the U(1), SU(2) and SU(3) gaugino Majorana mass parameters are equal, *i.e.*, $M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}$. This implies that the *low-energy* gaugino mass parameters satisfy:

$$M_3 = \frac{g_3^2}{g_2^2} M_2 \simeq 3.5 M_2, \qquad M_1 = \tfrac{5}{3} \tan^2 \theta_W M_2 \simeq 0.5 M_2 \,. \qquad (1)$$

The other two mSUGRA parameters are the supersymmetric Higgs mass parameter $\mu$ and an off-diagonal soft Higgs squared-mass. After the imposition of electroweak symmetry breaking, these two parameters can be traded in for the two Higgs vacuum expectation values (modulo a sign ambiguity in $\mu$). By fixing the $Z$ mass, the remaining mSUGRA parameters are determined by the ratio of Higgs vacuum expectation values ($\tan\beta$) and the sign of $\mu$. The lightest supersymmetric particle (LSP) is nearly always the lightest neutralino (denoted in this chapter by $\widetilde{\chi}_1^0$). Non-minimal extensions of the mSUGRA model have also been considered in which some of the parameter universality assumptions have been relaxed.

In GMSB models [6], $\sqrt{F}$ is suffiently small that the $\widetilde{g}_{3/2}$ is almost always the lightest supersymmetric particle (LSP) and plays a prominent phenomenological role. Then, different choices for the next-to-lightest supersymmetric particle (NLSP) lead to different phenomenologies. In the simplest GMSB models, the gaugino and scalar soft-supersymmetry-breaking masses are given by SU(3), SU(2) and U(1) gauge group factors times an overall scale $\Lambda$, while the $A$ parameters are expected to be negligible. [The low-energy values of the gaugino mass parameters also satisfy Eq. (1).] The parameter set is then completed by $\tan\beta$ and sign($\mu$).

Finally, one can also consider alternative low-energy supersymmetric approaches. For example, if R-parity violation (RPV) is present [7], additional supersymmetric parameters are introduced. These include parameters $\lambda_L$, $\lambda'_L$ and $\lambda_B$ which govern new lepton and baryon number violating scalar-fermion Yukawa couplings derived from the following supersymmetic interactions:

$$(\lambda_L)_{pmn} \widehat{L}_p \widehat{L}_m \widehat{E}_n^c + (\lambda'_L)_{pmn} \widehat{L}_p \widehat{Q}_m \widehat{D}_n^c + (\lambda_B)_{pmn} \widehat{U}_p^c \widehat{D}_m^c \widehat{D}_n^c \,, \qquad (2)$$

where $p$, $m$, and $n$ are generation indices, and gauge group indices are suppressed. In the notation above, the "superfields" $\widehat{Q}$, $\widehat{U}^c$, $\widehat{D}^c$, $\widehat{L}$, and $\widehat{E}^c$ respectively represent $(u,d)_L$, $u_L^c$, $d_L^c$, $(\nu, e^-)_L$, and $e_L^c$ and the corresponding superpartners. The Yukawa interactions are obtained from Eq. (2) by taking all possible combinations involving two fermions and one scalar superpartner.

## 2  Classes of Supersymmetric Signals

The lack of knowledge of the origin and structure of the supersymmetry-breaking parameters implies that the predictions for low-energy supersymmetry and the consequent phenomenology depend on a plethora of unknown parameters. Nevertheless, we can broadly classify supersymmetric signals at future colliders by considering a variety of theoretical approaches. In this section, we delineate the possible supersymmetric signatures, and in the next section we explore their consequences for experimentation at future colliders.

### 2.1  Missing energy signatures

In R-parity-conserving low-energy supersymmetry, supersymmetric particles are produced in pairs. The subsequent decay of a heavy supersymmetric particle generally proceeds via a multistep decay chain [8,9,10], ending in the production of at least one supersymmetric particle that (in conventional models) is weakly interacting and escapes the collider detector. Thus, supersymmetric particle production yields events that contain at least two escaping non-interacting particles, leading to a missing energy signature. At hadron colliders, it is only possible to detect missing transverse energy ($E_T^{\rm miss}$), since the center-of-mass energy of the hard collision is not known on an event-by-event basis.

In conventional SUGRA-based models, the weakly-interacting LSP's that escape the collider detector (which yields large missing transverse energy) are accompanied by energetic jets and/or leptons. This is the "smoking-gun" signature of low-energy supersymmetry. However, there are two unconventional approaches in which the smoking-gun signature is absent. First, consider a model in which the $\widetilde{\chi}_1^0$ is the LSP but the lightest neutralino and chargino are nearly degenerate in mass. If the mass difference is $\lesssim 100$ MeV, then $\widetilde{\chi}_1^+$ is long-lived and decays outside the detector [11,12]. In this case, some supersymmetric events would yield *no* missing energy and two semi-stable charged particles that pass through the detector. Second, there are models in which a gluino (more precisely, the $R^0 = \widetilde{g}g$ bound state) is the LSP [b]. A massive $R^0$ is likely to simply pass through the detector without depositing significant energy. Even when it is light enough to be stopped, the hadronic calorimeter will measure only the kinetic energy of the $R^0$. In either case, there would be

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[b]Farrar has advocated the existence of a very light gluino with a mass less than a few GeV [13]. Recent experimental data [14] show no evidence for a such a light gluino, although the assertion that light gluinos are definitively ruled out is still in dispute. The possibility of a more massive LSP gluino in SUGRA-based models has been considered in Ref. [12].

substantial missing energy [15]. However, there would be no jets arising from $\widetilde{g}$ decays in such models.

In conventional GMSB models with a gravitino-LSP[c], all supersymmetric events contain at least two NLSP's, and the resulting signature depends on the NLSP properties. Four physically distinct possible scenarios emerge:

- The NLSP is electrically and color neutral and long-lived, and decays outside of the detector to its associated Standard Model partner and the gravitino.

- The NLSP is the sneutrino and decays invisibly into $\nu\widetilde{g}_{3/2}$ either inside or outside the detector.

In either of these two cases, the resulting missing-energy signal is similar to that of the SUGRA-based models where $\widetilde{\chi}_1^0$ or $\widetilde{\nu}$ is the LSP.

- The NLSP is the $\widetilde{\chi}_1^0$ and decays inside the detector to $N\widetilde{g}_{3/2}$, where $N = \gamma$, $Z$ or a neutral Higgs boson.

In this case, the gravitino-LSP behaves like the neutralino or sneutrino LSP of the SUGRA-based models. However, in contrast to SUGRA-based models, the missing energy events of the GMSB-based model are characterized by the associated production of (at least) two $N$'s, one for each NLSP[d]. Note that if $\widetilde{\chi}_1^0$ is lighter than the $Z$ and $h^0$ then BR($\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{g}_{3/2}$) = 100%, and all supersymmetric production will result in missing energy events with at least two associated photons.

- The NLSP is a charged slepton (typically $\widetilde{\tau}_R$ in GMSB models if $m_{\widetilde{\tau}_R} < m_{\widetilde{\chi}_1^0}$), which decays to the corresponding lepton partner and gravitino.

If the decay is prompt, then one finds missing energy events with associated leptons (taus). If the decay is not prompt, one observes a long-lived heavy semi-stable charged particle with *no* associated missing energy (prior to the decay of the NLSP).

There are also GMSB scenarios in which there are several nearly degenerate so-called co-NLSP's [17], any one of which can be produced at the penultimate step of the supersymmetric decay chain[e]. The resulting supersymmetric signals

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[c]It is also possible to construct a GMSB scenario in which the $\widetilde{g}$ is the LSP [16]. The resulting phenomenology corresponds to that of the massive gluino LSP discussed above.

[d]If the decay of the NLSP is not prompt, it is possible to produce events in which one NLSP decays inside the detector and one NLSP decays outside of the detector.

[e]For example, if $\widetilde{\tau}_R^\pm$ and $\widetilde{\chi}_1^0$ are nearly degenerate in mass, then neither $\widetilde{\tau}_R^\pm \rightarrow \tau^\pm\widetilde{\chi}_1^0$ nor $\widetilde{\chi}_1^0 \rightarrow \widetilde{\tau}_R^\pm\tau^\mp$ are kinematically allowed decays. In this case, $\widetilde{\tau}_R^\pm$ and $\widetilde{\chi}_1^0$ are co-NLSP's, and each decays dominantly into its Standard Model superpartner plus a gravitino.

would consist of events with two (or more) co-NLSP's, each one of which would decay according to one of the four scenarios delineated above. For additional details on the phenomenology of the co-NLSP's, see Ref. [17].

In R-parity violating SUGRA-based models the LSP is unstable. If the RPV-couplings are sufficiently weak, then the LSP will decay outside the detector, and the standard missing energy signal applies. If the LSP decays inside the detector, the phenomenology of RPV models depends on the identity of the LSP and the branching ratio of possible final state decay products. If the latter includes a neutrino, then the corresponding RPV supersymmetric events would result in missing energy (through neutrino emission) in association with hadron jets and/or leptons. Other possibilities include decays into charged leptons in association with jets (with no neutrinos), and decays into purely hadronic final states. Clearly, these latter events would contain little missing energy. If R-parity violation is present in GMSB models, the RPV decays of the NLSP can easily dominate over the NLSP decay to the gravitino. In this case, the phenomenology of the NLSP resembles that of the LSP of SUGRA-based RPV models.

### 2.2   Lepton (e, μ and τ) signatures

Once supersymmetric particles are produced at colliders, they do not necessarily decay to the LSP (or NLSP) in one step. The resulting decay chains can be complex, with a number of steps from the initial decay to the final state [9]. Along the way, decays can produce real or virtual $W$'s, $Z$'s, charginos, neutralinos and sleptons, which then can produce leptons in their subsequent decays. Thus, many models yield large numbers of supersymmetric events characterized by one or more leptons in association with missing energy, with or without hadronic jets.

One signature of particular note is events containing like-sign di-leptons [18]. The origin of such events is associated with the Majorana nature of the gaugino. For example, $\widetilde{g}\widetilde{g}$ production followed by $\widetilde{g} \to q\overline{q}\widetilde{\chi}_1^{\pm} \to q\overline{q}\ell^{\pm}\nu\widetilde{\chi}_1^0$ can result in like-sign leptons since the $\widetilde{g}$ decay leads with equal probability to either $\ell^+$ or $\ell^-$. If the masses and mass differences are both substantial (which is typical in mSUGRA models, for example), like-sign di-lepton events will be characterized by fairly energetic jets and isolated leptons and by large $E_T^{\mathrm{miss}}$ from the LSP's. Other like-sign di-lepton signatures can arise in a similar way from the decay chains initiated by the heavier neutralinos.

Distinctive tri-lepton signals [19] can result from $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \to (\ell^{\pm}\nu\widetilde{\chi}_1^0)(\ell^+\ell^-\widetilde{\chi}_1^0)$. Such events have little hadronic activity (apart from initial state radiation of jets off the annihilating quarks at hadron colliders). These events can have a

variety of interesting characteristics depending on the fate of the final state neutralinos.

If the soft-supersymmetry breaking slepton masses are flavor universal at the high energy scale $M_X$ (as in mSUGRA models) and $\tan\beta \gg 1$, then the $\widetilde{\tau}_R$ will be significantly lighter than the other slepton states. As a result, supersymmetric decay chains involving (s)leptons will favor $\widetilde{\tau}_R$ production, leading to a predominance of events with multiple $\tau$-leptons in the final state.

In GMSB models with a charged slepton NLSP, the decay $\widetilde{\ell} \to \ell \, \widetilde{g}_{3/2}$ (if prompt) yields at least two leptons for every supersymmetric event in association with missing energy. In particular, in models with a $\widetilde{\tau}_R$ NLSP, supersymmetric events will characteristically contain at least two $\tau$'s.

In RPV models, decays of the LSP (in SUGRA models) or NLSP (in GMSB models) mediated by RPV-interactions proportional to $\lambda_L$ and $\lambda'_L$ will also yield supersymmetric events containing charged leptons. However, if the only significant RPV-interaction is the one proportional to $\lambda'_L$, then such events would *not* contain missing energy (in contrast to the GMSB signature described above).

### 2.3  b-quark signatures

The phenomenology of gluinos and squarks depends critically on their relative masses. If the gluino is heavier, it will decay dominantly into $q\widetilde{q}$ [f], while the squark can decay into quark plus chargino or neutralino. If the squark is heavier, it will decay dominantly into a quark plus gluino, while the gluino will decay into the three-body modes $q\bar{q}\widetilde{\chi}$ (where $\widetilde{\chi}$ can be either a neutralino or chargino, depending on the charge of the final state quarks). A number of special cases can arise when the possible mass splitting among squarks of different flavors is taken into account. For example, models of supersymmetric mass spectra have been considered where the third generation squarks are lighter than the squarks of the first two generations. If the gluino is lighter than the latter but heavier than the former, then the only open gluino two-body decay mode could be $b\widetilde{b}$ [g]. In such a case, all $\widetilde{g}\widetilde{g}$ events will result in at least four $b$-quarks in the final state (in associated with the usual missing energy signal, if appropriate). More generally, due to the flavor independence of the strong interactions, one expects three-body gluino decays into $b$-quarks in at least

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[f] In this section, we employ the notation $q\widetilde{q}$ to mean either $q\bar{\widetilde{q}}$ or $\bar{q}\widetilde{q}$.

[g] Although one top-squark mass-eigenstate ($\widetilde{t}_1$) is typically lighter than $\widetilde{b}$ in models, the heavy top-quark mass may result in a kinematically forbidden gluino decay mode into $t\widetilde{t}_1$.

20% of all gluino decays[h]. Additional $b$-quarks can arise from both top-quark and top-squark decays, and from neutral Higgs bosons produced somewhere in the chain decays [20]. Finally, at large $\tan\beta$, the enhanced Yukawa coupling to $b$-quarks can increase the rate of $b$-quark production in neutralino and chargino decays occurring at some step in the gluino chain decay.

These observations suggest that many supersymmetric events at hadron colliders will be characterized by $b$-jets in association with missing energy [10,21,22].

### 2.4  Signatures involving photons

In mSUGRA models, most supersymmetric events do not contain isolated energetic photons. However, some areas of low-energy supersymmetric parameter space do exist in which final state photons can arise in the decay chains of supersymmetric particles. If one relaxes the condition of gaugino mass unification, then the *low-energy* gaugino mass parameters no longer must satisfy Eq. (1). As a result, interesting alternative supersymmetric phenomenologies can arise. For example, if the low-energy mass parameters satisfy $M_1 \simeq M_2$, then the branching ratio for $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 \gamma$ can be significant [23]. In the model of Ref. [24], the $\widetilde{\chi}_1^0$-LSP is dominantly higgsino, while $\widetilde{\chi}_2^0$ is dominantly gaugino. Thus, many supersymmetric decay chains end in the production of $\widetilde{\chi}_2^0$, which then decays to $\widetilde{\chi}_1^0 \gamma$. In this picture, the pair production of supersymmetric particles often yields two photons plus associated missing energy. At LEP-2, one can also produce $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0$ which would then yield single photon events in association with large missing energy.

In GMSB models with a $\widetilde{\chi}_1^0$-NLSP, all supersymmetric decay chains would end up with the production of $\widetilde{\chi}_1^0$. Assuming that $\widetilde{\chi}_1^0$ decays inside the collider detector, one possible decay mode is $\widetilde{\chi}_1^0 \to \gamma \widetilde{g}_{3/2}$. In many models, the branching ratio for this radiative decay is significant (and could be as high as 100% if other possible two-body decay modes are not kinematically allowed). In the latter case, supersymmetric pair production would also yield events with two photons in associated with large missing energy. The characteristics of these events differ in detail from those of the corresponding events expected in the model of Ref. [24].

### 2.5  Kinks and long-lived heavy particles

In most SUGRA-based models, all supersymmetric particles in the decay chain decay promptly until the LSP is reached. The LSP is exactly stable and escapes

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[h]Here we assume the approximate degeneracy of the first two generations of squarks, as suggested from the absence of flavor-changing neutral-current decays. In many models, the $b$-squarks tend to be of similar mass or lighter than the squarks of the first two generations.

the collider detector. However, exceptions are possible. In particular, if there is a supersymmetric particle that is just barely heavier than the LSP, then its (three-body) decay rate to the LSP will be significantly suppressed and it could be long lived. For example, in the models with $|\mu| \gg M_1 > M_2$ [11,12] implying $m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_1^0}$, the $\widetilde{\chi}_1^\pm$ can be sufficiently long lived to yield a detectable vertex, or perhaps even exit the detector.

In GMSB models, the NLSP may be long-lived, depending on its mass and the scale of supersymmetry breaking, $\sqrt{F}$. The NLSP is unstable and eventually decays to the gravitino. For example, in the case of the $\widetilde{\chi}_1^0$-NLSP (which is dominated by its U(1)-gaugino component), one finds $\Gamma(\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}) = m_{\widetilde{\chi}_1^0}^5 \cos^2\theta_W / 16\pi F^2$. It then follows that

$$(c\tau)_{\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}} \simeq 130 \left(\frac{100 \text{ GeV}}{m_{\widetilde{\chi}_1^0}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4 \mu\text{m}. \tag{3}$$

For simplicity, assume that $\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}$ is the dominant NLSP decay mode. If $\sqrt{F} \sim 10^4$ TeV, then the decay length for the NLSP is $c\tau \sim 10$ km for $m_{\widetilde{\chi}_1^0} = 100$ GeV; while $\sqrt{F} \sim 100$ TeV implies a short but vertexable decay length. A similar result is obtained in the case of a charged NLSP. Thus, if $\sqrt{F}$ is sufficiently large, the charged NLSP will be semi-stable and may decay outside of the collider detector.

Finally, if R-parity violation is present, the decay rate of the LSP in SUGRA-based models (or the NLSP in R-parity-violating GMSB models) could be in the relevant range to yield visible secondary vertices.

## 3    Supersymmetry searches at future colliders

In this section, we consider the potential for discovering low-energy supersymmetry at future colliders. A variety of supersymmetric signatures have been reviewed in Section 2, and we now apply these to supersymmetry searches at future colliders. Ideally, experimental studies of supersymmetry should be as model-independent as possible. Ultimately, the goal of experimental studies of supersymmetry is to measure as many of the 124 MSSM parameters (and any additional parameters that can arise in non-minimal extensions) as possible. In practice, a fully general analysis will be difficult, particularly during the initial supersymmetry discovery phase. Thus, we focus the discussion in this section on the expected phenomenology of supersymmetry at the various future facilities under a number of different model assumptions. Eventually, if candidates for supersymmetric phenomena are discovered, one would utilize precision ex-

perimental measurements to map out the supersymmetric parameter space and uncover the structure of the underlying supersymmetry-breaking.

### 3.1 SUGRA-based models

We begin with the phenomenology of mSUGRA. Of particular importance are the relative sizes of the different supersymmetric particle masses. Generic properties of the resulting superpartner mass spectrum are discussed in Ref. [2]. An important consequence of the mSUGRA mass spectrum is that substantial phase space is available for most decays occurring at each step in a given chain decay of a heavy supersymmetric particle.

Extensive Monte Carlo studies have examined the region of mSUGRA parameter space for which direct discovery of supersymmetric particles at the Tevatron and the LHC will be possible [25]. At the hadron colliders, the ultimate supersymmetric mass reach is determined by the searches for both the strongly-interacting superpartners (squarks and gluinos) and the charginos/neutralinos. Cascade decays of the produced squarks and gluinos lead to events with jets, missing energy, and various numbers of leptons. Pair production of charginos and/or neutralinos can produce distinctive multi-lepton signatures. The chargino/neutralino searches primarily constrain the mSUGRA parameter $m_{1/2}$, which can be translated into an equivalent bound on the gluino mass. As a result, gluino and squark masses up to about 400 GeV can be probed at the upcoming Tevatron Run-II; further improvements are projected at the proposed TeV-33 upgrade [26], where supersymmetric masses up to about 600 GeV can be reached. The maximum reach at the LHC is generally attained by searching for the $1\ell + \text{jets} + E_T^{\text{miss}}$ channel; one will be able to discover squarks and gluinos with masses up to several TeV [20]. Some particularly important classes of events include:

- $pp \to \widetilde{g}\widetilde{g} \to \text{jets} + E_T^{\text{miss}}$ and $pp \to \widetilde{g}\widetilde{g} \to \ell^{\pm}\ell^{\pm} + \text{jets} + E_T^{\text{miss}}$ (the like-sign dilepton signal [18]). The mass difference $m_{\widetilde{g}} - m_{\widetilde{\chi}_1^{\pm}}$ can be determined from jet spectra end points, while $m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^0}$ can be roughly determined by analyzing various distributions of kinematic observables in the like-sign channel [18,21,27]. An absolute scale for $m_{\widetilde{g}}$ can be estimated (within an accuracy of roughly $\pm 15\%$) by separating the like-sign events into two hemispheres corresponding to the two $\widetilde{g}$'s [18], by a similar separation in the jets+$E_T^{\text{miss}}$ channel [20], or variations thereof [21,27].

- $pp \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \to (\ell^{\pm}\nu\widetilde{\chi}_1^0)(\ell^+\ell^-\widetilde{\chi}_1^0)$, which yields a tri-lepton + $E_T^{\text{miss}}$ final

state. The mass difference $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ is easily determined $^i$ if enough events are available [19].

- $pp \to \widetilde{\ell}\widetilde{\ell} \to 2\ell + E_T^{\text{miss}}$, detectable at the LHC for $m_{\widetilde{\ell}} \lesssim 300$ GeV [20].

- Squarks will be pair produced and, for $m_0 \gg m_{1/2}$, would lead to $\widetilde{g}\widetilde{g}$ events with two extra jets emerging from the primary $\widetilde{q} \to q\widetilde{g}$ decays.

The LHC provides significant opportunities for precision measurements of the mSUGRA parameters [21]. In general, one expects large samples of supersymmetric events with distinguishing features that allow an efficient separation from Standard Model backgrounds. The biggest challenge in analyzing these events may be in distinguishing one set of supersymmetric signals from another. Within the mSUGRA framework, the parameter space is small enough to permit the untangling of the various signals and allows one to extract the mSUGRA parameters with some precision.

Important discovery modes at the NLC include the following [28]:

- $e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to (q\bar{q}\widetilde{\chi}_1^0$ or $\ell\nu\widetilde{\chi}_1^0) + (q\bar{q}\widetilde{\chi}_1^0$ or $\ell\nu\widetilde{\chi}_1^0)$;

- $e^+e^- \to \widetilde{\ell}^+\widetilde{\ell}^- \to (\ell^+\widetilde{\chi}_1^0$ or $\overline{\nu}\widetilde{\chi}_1^+) + (\ell^-\widetilde{\chi}_1^0$ or $\nu\widetilde{\chi}_1^-)$.

In both cases, the masses of the initially produced supersymmetric particles as well as the final state neutralinos and charginos will be well-measured. Here, one is able to make use of the energy spectra end points and beam energy constraints to make precision measurements of masses and determine the underlying supersymmetric parameters. Polarization of the beams is an essential tool that can be used to enhance signals while suppressing Standard Model backgrounds. Moreover, polarization can be employed to separate out various supersymmetric contributions in order to explore the inherent chiral structure of the interactions. The supersymmetric mass reach is limited by the center-of-mass energy of the NLC. For example, if the scalar mass parameter $m_0$ is too large, squark and slepton pair production will be kinematically forbidden. To probe values of $m_0 \sim 1$—1.5 TeV requires a collider energy in the range of $\sqrt{s} \gtrsim 2$—3 TeV. It could be that such energies will be more easily achieved at a future $\mu^+\mu^-$ collider.

The strength of the lepton colliders lies in the ability to analyze supersymmetric signals and make precision measurements of observables. Ideally, one would like to measure the underlying supersymmetric parameters without

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$^i$In some cases, $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ can still be determined if $\widetilde{\chi}_2^0$ is produced at some step in a supersymmetric decay chain.

prejudice. One could then test the model assumptions, and study possible deviations. The most efficient way to carry out such a program is to set the lepton collider center-of-mass energy to the appropriate value of $\sqrt{s}$ in order to first study the light supersymmetric spectrum (lightest charginos and neutralinos and sleptons). In this way, one limits the interference among competing supersymmetric signals. Experimentation at the lepton colliders then can provide model-independent measurements of the associated underlying supersymmetric parameters. Once these parameters are ascertained, one can analyze with more confidence events with heavy supersymmetric particles decaying via complex decay chains. Thus, the NLC and LHC supersymmetric searches are complementary.

Beyond mSUGRA, the MSSM parameter space becomes more complex. It is possible to perturb the mSUGRA model by adding some non-universality among the scalar mass parameters without generating phenomenologically unacceptable flavor changing neutral currents. There has been no systematic analysis of the resulting phenomenology at future colliders. (The implications of non-universal scalar masses for LHC phenomenology were briefly addressed in Ref. [22].) Nevertheless, the possible non-degeneracy of squarks could have a significant impact on the search for squarks at hadron colliders. In particular, in mSUGRA models one typically finds that four flavors of squarks (with two squark eigenstates per flavor) and $\widetilde{b}_R$ are nearly mass-degenerate, while the masses of $\widetilde{b}_L$ and the top-squark mass eigenstates could be significantly different [j]. This means that the *observed* cross-section for the production of squark pairs at hadron colliders would be enhanced by a multiplicity factor of eight or larger (depending on the number of approximately mass-degenerate squark species). Clearly, if some of the first and second generation squarks are split in mass, the relevant effective cross-sections are smaller. This could lead to more background contamination of squark signals at hadron colliders. The impact of squark non-degeneracy on the discovery mass reach for squarks at the Tevatron and LHC has not yet been analyzed.

It is also possible to introduce arbitrary non-universal gaugino mass parameters (at the high-energy scale). For example, suppose that the non-universal gaugino masses at the high-energy scale imply that the gaugino mass parameters at the low-energy scale satisfy $M_2 < M_1$, *i.e.*, the SU(2)-gaugino component is dominant in the lightest chargino and neutralino [11,12]. In this case, the $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$ can be closely degenerate, in which case the visible decay products in $\widetilde{\chi}_1^+ \to \widetilde{\chi}_1^0 + X$ decays will be very soft and difficult to detect. Con-

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[j]If $\tan\beta \gg 1$, then $\widetilde{b}_L$–$\widetilde{b}_R$ mixing can be significant, in which case the two bottom-squark mass eigenstates could also be significantly split in mass from the first two generations of squarks.

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sequences for chargino and neutralino detection in $e^+e^-$ and $\mu^+\mu^-$ collisions, including the importance of the $e^+e^- \to \gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ production channel, are discussed in Refs. [11,12]. There is also the possibility that $m_{\widetilde{g}} \sim m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_1^0}$. The decay products in the $\widetilde{g}$ decay chain would then be very soft, and isolation of $\widetilde{g}\widetilde{g}$ events would be much more difficult at hadron colliders than in the usual mSUGRA case. In particular, hard jets in association with missing energy would be much rarer, since they would only arise from initial state radiation. The corresponding reduction in supersymmetric parameter space coverage at the Tevatron Main Injector is explored in Ref. [12].

As a second example, consider the case where the low-energy gaugino mass parameters satisfy $M_2 \sim M_1$ [k]. If we also assume that $\tan\beta \sim 1$ and $|\mu| < M_1$, $M_2$ [l], then the lightest two neutralinos are nearly a pure photino and higgsino respectively, *i.e.*, $\widetilde{\chi}_2^0 \simeq \widetilde{\gamma}$ and $\widetilde{\chi}_1^0 \simeq \widetilde{H}$. For this choice of MSSM parameters, one finds that the rate for the one-loop decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ dominates over all tree level decays of $\widetilde{\chi}_2^0$ and $\mathrm{BR}(\widetilde{e} \to e\widetilde{\chi}_2^0) \gg \mathrm{BR}(\widetilde{e} \to e\widetilde{\chi}_1^0)$. Clearly, the resulting phenomenology [24] differs substantially from mSUGRA expectations. This scenario was inspired by the CDF $ee\gamma\gamma$ event [29]. Suppose that the $ee\gamma\gamma$ event resulted from $\widetilde{e}\widetilde{e}$ production, where $\widetilde{e} \to e\widetilde{\chi}_2^0 \to e\gamma\widetilde{\chi}_1^0$. Then in the model of Ref. [24], one would expect a number of other distinctive supersymmetric signals to be observable at LEP-2 (running at its maximal energy) and at Run-II of the Tevatron. In particular, LEP-2 would expect events of the type: $\ell\ell + X + E_T^{\mathrm{miss}}$ and $\gamma\gamma + X + E_T^{\mathrm{miss}}$, while Tevatron would expect events of the type: $\ell\ell + X + E_T^{\mathrm{miss}}$, $\gamma\gamma + X + E_T^{\mathrm{miss}}$, $\ell\gamma + X + E_T^{\mathrm{miss}}$, $\ell\ell\gamma + X + E_T^{\mathrm{miss}}$, $\ell\gamma\gamma + X + E_T^{\mathrm{miss}}$, and $\ell\ell\ell + X + E_T^{\mathrm{miss}}$. In the above signatures, $X$ stands for additional leptons, photons, and/or jets. These signatures can also arise in GMSB models, although the kinematics of the various events can often be distinguished.

### 3.2  GMSB-based models

The collider signals for GMSB models depend critically on the NLSP identity and its lifetime (or equivalently, its decay length). Thus, we examine the phenomenology of both promptly-decaying and longer-lived NLSP's. In the latter case, the number of decays where one or both NLSP's decay within a radial distance $R$ is proportional to $[1 - \exp(-2R/c\tau)] \simeq 2R/(c\tau)$. For large $c\tau$, most decays would be non-prompt, with many occurring in the outer parts

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[k]We remind the reader that gaugino mass unification at the high-energy scale would predict $M_2 \simeq 2M_1$.

[l]To achieve such a small $\mu$-parameter requires, *e.g.*, some non-universality among scalar masses of the form $m_{H_1}^2 \neq m_{\widetilde{q}}^2, m_{\widetilde{\ell}}^2$.

of the detector or completely outside the detector. To maximize sensitivity to GMSB models and fully cover the $(\sqrt{F}, \Lambda)$ parameter space, we must develop strategies to detect decays that are delayed, but not necessarily so delayed as to be beyond current detector coverage and/or specialized extensions of current detectors.

In the discussion below, we focus on various cases, where the NLSP is a neutralino dominated by its U(1)-gaugino ($\widetilde{B}$) or Higgsino ($\widetilde{H}$) components, and where the NLSP is the lightest charged slepton (usually the $\widetilde{\tau}_R$). We first address the case of prompt decays, and then indicate the appropriate strategies for the case of the longer-lived NLSP.

- **Promptly-decaying NLSP: $\widetilde{\chi}_1^0 \simeq \widetilde{B}$**

We focus on the production of the neutralinos, charginos, and sleptons since these are the lightest of the supersymmetric particles in the GMSB models. The possible decays of the NLSP in this case are: $\widetilde{B} \to \gamma \widetilde{g}_{3/2}$ or $\widetilde{B} \to Z \widetilde{g}_{3/2}$. The latter is only relevant for the case of a heavier NLSP (and moreover is suppressed by $\tan^2 \theta_W$). It will be ignored in the following discussion.

At hadronic colliders, the $\widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ production rate is small, but rates for $\widetilde{\chi}_1^+ \widetilde{\chi}_1^- \to W^{(\star)} W^{(\star)} \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to W^{(\star)} W^{(\star)} \gamma\gamma + E_T^{\text{miss}}$, $\widetilde{\ell}_R \widetilde{\ell}_R \to \ell^+ \ell^- \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to \ell^+ \ell^- \gamma\gamma + E_T^{\text{miss}}$, $\widetilde{\ell}_L \widetilde{\ell}_L \to \ell^+ \ell^- \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to \ell^+ \ell^- \gamma\gamma + E_T^{\text{miss}}$, *etc.* will all be substantial. Implications for GMSB phenomenology at the Tevatron can be found in Refs. [30,31,32]. It is possible to envision GMSB parameters such that the $ee\gamma\gamma + E_T^{\text{miss}}$ CDF event [29] corresponds to selectron pair production followed by $\widetilde{e} \to e \widetilde{\chi}_1^0$ with $\widetilde{\chi}_1^0 \to \gamma \widetilde{g}_{3/2}$ [30,24,32,33]. However, in this region of GMSB parameter space, other supersymmetric signals should be prevalent, such as $\widetilde{\nu}_L \widetilde{\ell}_L \to \ell \gamma\gamma + E_T^{\text{miss}}$ and $\widetilde{\nu}_L \widetilde{\nu}_L \to \gamma\gamma + E_T^{\text{miss}}$. The $\widetilde{\chi}_2^0 \widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ rates would also be significant and lead to $X\gamma\gamma + E_T^{\text{miss}}$ with $X = \ell^\pm, \ell^+ \ell'^-, \ell^+ \ell^- \ell'^\pm$. Limits on these event rates from current CDF and D0 data already eliminate much, if not all, of the parameter space that could lead to the CDF $ee\gamma\gamma$ event [34].

At LEP-2/NLC [35], the rate for the simplest signal, $e^+ e^- \to \widetilde{\chi}_1^0 \widetilde{g}_{3/2} \to \gamma + E_T^{\text{miss}}$, is expected to be very small. A more robust channel is $e^+ e^- \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to \gamma\gamma + E_T^{\text{miss}}$ with a (flat) spectrum of photon energies in the range $\frac{1}{4}\sqrt{s}(1 - \beta) \leq E_\gamma \leq \frac{1}{4}\sqrt{s}(1 + \beta)$.

- **Promptly decaying NLSP: $\widetilde{\chi}_1^0 \simeq \widetilde{H}$**

The possible decays of the NLSP in this case are: $\widetilde{H} \to \widetilde{g}_{3/2} + h^0, H^0, A^0$, depending on the Higgs masses. If the corresponding two-body decays are

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not kinematically possible, then three-body decays (where the corresponding Higgs state is virtual) may become relevant. However, in realistic cases, one expects $\widetilde{\chi}_1^0$ to contain small but non-negligible gaugino components, in which case the rate for $\widetilde{\chi}_1^0 \to \widetilde{g}_{3/2}\gamma$ would dominate all three-body decays. In what follows, we assume that the two-body decay $\widetilde{H} \to \widetilde{g}_{3/2}h^0$ is kinematically allowed and dominant. The supersymmetric signals that would emerge at both Tevatron/LHC and LEP-2/NLC would then be $4b + X + E_T^{\mathrm{miss}}$ final states, where $X$ represents the decay products emerging from the cascade chain decays of the more massive supersymmetric particles. Of course, at LEP-2/NLC direct production of higgsino pairs, $e^+e^- \to \widetilde{H}\widetilde{H}$ (via virtual $s$-channel $Z$-exchange) would be possible in general, leading to pure $4b + E_T^{\mathrm{miss}}$ final states.

## • Promptly decaying NLSP: $\widetilde{\ell}_R$

The dominant slepton decay modes are: $\widetilde{\ell}_R^\pm \to \ell^\pm \widetilde{g}_{3/2}$ and $\widetilde{\ell}_L^\pm \to \ell^\pm \widetilde{\chi}_1^{0\star} \to \ell^\pm (\widetilde{\ell}_R^\pm \ell^\mp)' \to \ell^\pm (\ell^\pm \ell^\mp)' \widetilde{g}_{3/2}$. The $\widetilde{\chi}_1^0$ will first decay to $\ell\widetilde{\ell}_L$ and $\ell\widetilde{\ell}_R$, followed by the above decays.

At both the Tevatron/LHC and LEP-2/NLC, typical pair production events will end with $\widetilde{\ell}_R\widetilde{\ell}_R \to \ell^+\ell^- + E_T^{\mathrm{miss}}$, generally in association with a variety of cascade chain decay products. The lepton energy spectrum will be flat in the $\widetilde{\ell}_R\widetilde{\ell}_R$ center of mass. Of course, pure $\widetilde{\ell}_R\widetilde{\ell}_R$ production is possible at LEP/NLC and the $\widetilde{\ell}_R\widetilde{\ell}_R$ center of mass would be the same as the $e^+e^-$ center of mass. Other simple signals at LEP/NLC, would include $\widetilde{\ell}_L\widetilde{\ell}_L \to 6\ell + E_T^{\mathrm{miss}}$.

If a slepton is the NLSP, it is most likely to be the $\widetilde{\tau}_R$. If this state is sufficiently lighter than the $\widetilde{e}_R$ and $\widetilde{\mu}_R$, then $\widetilde{e}_R \to e\widetilde{\tau}_R\tau$ and $\widetilde{\mu}_R \to \mu\widetilde{\tau}_R\tau$ decays (via the $\widetilde{B}$ component of the mediating virtual neutralino) might dominate over the direct $\widetilde{e}_R \to e\widetilde{g}_{3/2}$ and $\widetilde{\mu}_R \to \mu\widetilde{g}_{3/2}$ decays, and all final states would cascade to $\tau$'s. The relative importance of these different possible decays has been examined in Ref. [17]. A study of this scenario at LEP-2 has been performed in Ref. [36].

## • Longer-lived NLSP: $\widetilde{\ell}_R$

If the $\widetilde{\ell}_R$ mainly decays before reaching the electromagnetic calorimeter, then one should look for a charged lepton that suddenly appears a finite distance from the interaction region, with non-zero impact parameter as measured by either the vertex detector or the electromagnetic calorimeter. Leading up to this decay would be a heavily ionizing track with $\beta < 1$ (as could be measured if a magnetic field is present).

If the $\widetilde{\ell}_R$ reaches the electromagnetic and hadronic calorimeters, then it behaves much like a heavy muon, presumably interacting in the muon chambers

or exiting the detector if it does not decay first. Limits on such objects should be pursued. There will be many sources of $\widetilde{\ell}_R$ production, including direct slepton pair production, and cascade decays resulting from the production of gluinos, squarks, and charginos [37]. Based on current Tevatron data, a charged pseudo-stable $\widetilde{\ell}_R$ can be ruled out with a mass up to about 80–100 GeV. Similar limits can probably be extracted from LEP-2 data.

- ### Longer-lived NLSP: $\widetilde{\chi}_1^0$

This is a much more difficult case. As before, we assume that the dominant decay of the NLSP in this case is $\widetilde{\chi}_1^0 \rightarrow \gamma \widetilde{g}_{3/2}$. Clearly, the sensitivity of detectors to delayed $\gamma$ appearance signals will be of great importance. If the $\widetilde{\chi}_1^0$ escapes the detector before decaying, then the corresponding missing energy signatures are the same as those occurring in SUGRA-based models.

At the Tevatron, standard supersymmetry signals (*e.g.*, jets or tri-leptons plus $E_T^{\text{miss}}$) are viable if $\Lambda \lesssim$ 30–70 TeV (given an integrated luminosity of $L = 0.1$–$30 \text{ fb}^{-1}$) independent of the magnitude of $\sqrt{F}$ [38,39]. Meanwhile, the prompt $\widetilde{\chi}_1^0 \rightarrow \gamma \widetilde{g}_{3/2}$ decay signals discussed earlier are viable only in a region defined by $\sqrt{F} \lesssim 500$ TeV at low $\Lambda$, rising to $\sqrt{F} \lesssim 1000$ TeV at $\Lambda \sim 120$ TeV [38,39]. This leaves a significant region of $(\sqrt{F}, \Lambda)$ parameter space that can only be probed by the delayed $\widetilde{\chi}_1^0 \rightarrow \gamma \widetilde{g}_{3/2}$ decays [38,39].

The ability to search for delayed-decay signals is rather critically dependent upon the detector design. The possible signals include the following [38,39]: (i) looking for isolated energy deposits (due to the $\gamma$ from the $\widetilde{\chi}_1^0$ decay) in the outer hadronic calorimeter cells of the D0 detector; (ii) searching for events where the delayed-decay photon is identified by a large (transverse) impact parameter as it passes into the electromagnetic calorimeter; and (iii) looking for delayed decays where the photon first emerges outside the main detector and is instead observed in a scintillator array (or similar device) placed at a substantial distance from the detector. The observed signal will always contain missing energy from one or more emitted gravitinos and/or from $\widetilde{\chi}_1^0$'s that do not decay inside the detector. Thus, by requiring large missing energy, the backgrounds can be greatly reduced while maintaining good efficiency for the GMSB signal. In combination, the above techniques may[m] allow the detection of supersymmetric particle production at the Tevatron in the GMSB parameter region $\sqrt{F} \lesssim 3000$ TeV and $\Lambda \lesssim 150$ TeV.

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[m]Event rates are significant even after very strong cuts on jets, photon energy and missing energy, but detailed background calculations remain to be done.

### 3.3   R-parity violating (RPV) models

In R-parity violating models, the LSP is no longer stable[n]. The relevant signals depend upon the nature of the LSP decay. The phenomenology depends on which R-parity violating couplings [Eq. (2)] are present. Only a brief discussion will be given here; for further details, see Ref. [7].

At the Tevatron and LHC [40], consider $\widetilde{g}\widetilde{g}$ production followed by gluino decay via the usual set of possible decay chains ending up with the LSP plus Standard Model particles. Until this point, all decays have involved only R-parity conserving interactions[o]. The RPV-interactions now enter in the decay of the LSP. We shall assume in the following discussion that the $\widetilde{\chi}_1^0$ is the LSP, although other possible choices can also be considered.

If $\lambda_B \neq 0$, then the dominant decay of $\widetilde{\chi}_1^0$ would result in the production of a three-jet final state ($\widetilde{\chi}_1^0 \to jjj$). The large jet backgrounds imply that we would need to rely on the like-sign dilepton signal (which would still be viable despite the absence of missing energy in the events). In general, this signal turns out to be sufficient for supersymmetry discovery out to gluino masses somewhat above 1 TeV. However, if the leptons of the like-sign dilepton signal are very soft, then the discovery reach would be much reduced[p]. This is one of the few cases where one could miss discovering low-energy supersymmetry at the LHC. If $\lambda_L$ dominates $\widetilde{\chi}_1^0$ decays, $\widetilde{\chi}_1^0 \to \mu^\pm e^\mp \nu, e^\pm e^\mp \nu$, and there would be many very distinctive multi-lepton signals. If $\lambda'_L$ is dominant, then $\widetilde{\chi}_1^0 \to \ell jj$ and again there would be distinctive multi-lepton signals.

More generally, many normally invisible events become visible. An important example is sneutrino pair production. Even if the dominant decay of the sneutrino is $\widetilde{\nu} \to \nu \widetilde{\chi}_1^0$ (which is likely if $m_{\widetilde{\nu}} > m_{\widetilde{\chi}_1^0}$), a visible signal emerges from the $\widetilde{\chi}_1^0$ decay as sketched above. Of course, for large enough $\lambda_L$ or $\lambda'_L$ the $\widetilde{\nu}$'s would have significant branching ratio for decay to charged lepton pairs or jet pairs, respectively. Indeed, such decays might dominate if $m_{\widetilde{\nu}} < m_{\widetilde{\chi}_1^0}$.

At LEP-2, NLC or the muon collider [41,42,43], the simplest process is

$$e^+ e^- \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to \underbrace{(jjj)(jjj)}_{\lambda_B}, \quad \underbrace{(\ell\ell\nu)(\ell\ell\nu)}_{\lambda_L}, \quad \underbrace{(\ell jj)(\ell jj)}_{\lambda'_L} \qquad (4)$$

(or the $\mu^+ \mu^-$ collision analogue), where the relevant RPV-coupling is indicated

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[n]We assume that the gravitino is not relevant for RPV phenomenology, as in SUGRA-based models.

[o]By assumption, the strengths of the R-parity conserving interactions are significantly larger than the corresponding RPV-interaction strengths.

[p]Soft leptons would occur in models where $m_{\widetilde{\chi}_1^\pm} \sim m_{\widetilde{\chi}_1^0}$, which requires non-universal gaugino masses [11,22].

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below the corresponding signal. Substantial rates for equally distinctive signals from production of more massive supersymmetric particles (including sneutrino pair production) would also be present. All these processes (if kinematically allowed) should yield observable supersymmetric signals. Some limits from LEP data already exist [44]. Of particular potential importance for non-zero $\lambda_L$ is $s$-channel resonant production of a sneutrino in $e^+e^-$ [42] and $\mu^+\mu^-$ [43] collisions. In particular, at $\mu^+\mu^-$ colliders this process is detectable down to quite small values of the appropriate $\lambda_L$, and could be of great importance as a means of actually determining the R-parity-violating couplings. Indeed, for small R-parity-violating couplings, absolute measurements of the couplings through other processes are extremely difficult. This is because such a measurement would typically require the R-parity-violating effects to be competitive with an R-parity-conserving process of known interaction strength. (For example, R-parity-violating neutralino branching ratios constrain only ratios of the R-parity-violating couplings.) Since sneutrino pair production would have been observed at the LHC, NLC and/or the muon collider, it would be easy to center on the sneutrino resonance in order to perform the crucial sneutrino factory measurements.

We end this section with two additional remarks. First, if the RPV coupling strengths are very small, then the RPV-violating decay of the LSP (*e.g.*, $\widetilde{\chi}_1^0$) could occur a substantial distance from the primary interaction point, but still within the detector (or at least not far outside the detector). The general techniques for detecting such delayed decays outlined at the end of Section 3.2 would again be relevant. It is particularly important to note that observation of the delayed decays would allow a determination of the absolute strengths of the RPV couplings. Second, one should not neglect the possibility that RPV couplings could be present in GMSB models. If the RPV couplings are substantial, then the RPV decays of the NLSP will dominate its R-parity-conserving decays into $\widetilde{g}_{3/2} + X$ [45], and all the RPV phenomenology described in this section will apply. For smaller RPV couplings, there could be competition between the RPV decays and the $\widetilde{g}_{3/2} + X$ decays of the NLSP.

## 4    Summary and Conclusions

Much effort has been directed at trying to develop strategies for precision measurements to establish the underlying supersymmetric structure of the interactions and to distinguish among models. However, we are far from understanding all possible facets of the most general MSSM parameter space (even restricted to those regions that are phenomenologically viable). Moreover, the phenomenology of non-minimal and alternative low-energy supersymmet-

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ric models (such as models with R-parity violation) and the consequences for collider physics have only recently begun to attract significant attention. The variety of possible non-minimal models of low-energy supersymmetry presents an additional challenge to experimenters who plan on searching for supersymmetry at future colliders.

If supersymmetry is discovered, it will provide a plethora of experimental signals and theoretical analyses. The many phenomenological manifestations and parameters of supersymmetry suggest that many years of experimental work will be required before it will be possible to determine the precise nature of supersymmetry-breaking and its implications for a more fundamental theory of particle interactions.

## Acknowledgements

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