Signals of a Sneutrino (N)LSP at the LHC

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Abstract

The sneutrino is a viable candidate for the NLSP in SUSY spectra with gravitino LSP. In this work we study the collider implications of this possibility. In particular, we investigate whether the LHC can distinguish it (at least, in some cases) from alternative spectra, such as those with a neutralino LSP. We show that there exists a complete family of experimentally allowed and theoretically motivated spectra with sneutrino NLSP, which exhibit very distinctive multilepton signals that are difficult to fake within the MSSM. We study these signals in detail, including the techniques necessary to find them. We demonstrate our analysis approach on simulations incorporating backgrounds.

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I. INTRODUCTION

Supersymmetry (SUSY) has been a leading framework for physics beyond the Standard Model (SM) for decades. While the basic motivation is quite simple – to stabilize the electroweak sector against quantum corrections from arbitrarily high energy scales – SUSY has proved to be a seemingly never-ending source of investigation from the perspective of formal theory, model building, and phenomenology. The vast parameter space of even the simplest incarnation, the Minimal Supersymmetric Standard Model (MSSM), leads to a large variety of possible collider and cosmological signals, many of which are not yet fully understood. In this paper, we turn our attention to some of the less-explored regions of the MSSM parameter space, regions where the sneutrino appears to be the lightest supersymmetric particle (LSP) from the perspective of colliders.

There are a couple of reasons why the sneutrino is typically overlooked as a possible LSP. In particular, it is unworkable as a dark matter candidate, since it would have already been discovered in direct detection experiments [1, 2]. There are of course many ways to model-build around the direct detection constraints, but by far the simplest is to assume that the sneutrino decays, either through \( R \)-parity-violating interactions or into a lighter gravitino. The role of dark matter must then be played either by the gravitino or by some other sector of particles. Putting the sneutrino near the bottom of the spectrum therefore appears to offer no “benefit.” However, even the standard scenario with a neutralino LSP is becoming progressively less viable (see, e.g., [3]), and we should definitely not take for granted that it is correct.

Cosmology aside, there is also a simple parametric bias that usually disfavors light sneutrinos. In both gravity mediation and gauge mediation (GMSB) [4–8], the masses of the sfermions acquire contributions proportional to gauge couplings. In more minimal scenarios, this tends to make the left-handed (LH) slepton doublet heavier than the right-handed (RH) slepton, as well as the bino and often the wino. However, as we will see in the next section, it is straightforward for the slepton doublet to end up much lighter when we go beyond minimal assumptions.

Though not often considered, then, there is no reason why the sneutrino cannot be at the bottom of the MSSM spectrum. Nonetheless, the most distinctive collider implications of this possibility remain mostly uninvestigated. If we assume that \( R \)-parity holds as a good...
symmetry, which is still very well-motivated from the perspective of forbidding proton decay, then the minimal cosmologically-viable scenario has the would-be LSP sneutrino decaying into the gravitino. However, since this decay is completely invisible, the sneutrino acts like an LSP in colliders, independent of its lifetime.\footnote{Our analysis will also trivially extend to those cases with $R$-parity violation where the sneutrino decays outside the detector.}

Here, we will begin an inquiry into the LHC signals of this sneutrino “(N)LSP”. We will find decay chain topologies and collider signatures that are noticeably different from the standard cases, such as a neutralino LSP.

Of course, even assuming a sneutrino NLSP with gravitino LSP, the parameter space describing the rest of the spectrum remains enormous. In our analysis here, we will concentrate on spectra with $O$(TeV) colored superparticles and lighter electroweak gauginos, all sitting above approximately flavor-degenerate LH slepton doublets. However, many of our observations will also survive in more generic spectra.

Given this setup, we can identify two broad classes of spectra which lead to somewhat different phenomenology: either the RH slepton participates in the decay chains, or it mostly does not. Roughly speaking, this depends on whether the RH slepton is heavier or lighter than the bino-like neutralino. In this paper, we will concentrate on the collider signatures of the simpler case where $m(\tilde{\tau}_R) > m(\tilde{B})$. We will investigate spectra with active RH sleptons in a companion paper \cite{9}.

In every decay chain ending in a sneutrino NLSP, lepton number is being carried away. This must necessarily be compensated for by release of a charged lepton or a neutrino. In addition, the sneutrino is quasi-degenerate with its $SU(2)_L$ partner, the charged LH slepton, so that the two sfermions will usually sit together at the bottom of the spectrum. This means that every decay chain has a sizable chance of producing at least one charged lepton, significantly modifying the lepton accounting compared to many alternative spectra.

In addition, the splitting within the slepton doublet is often large enough to produce visible particles via $W^*$ emission. In the leptonic mode, this can come in combination with a charged lepton produced with the slepton, leading to a rather unique excess of opposite-sign uncorrelated-flavor lepton pairs. This excess will be accompanied by somewhat larger number of completely sign- and flavor-uncorrelated dilepton events, as well as a somewhat
smaller number of very distinctive trilepton events. The coexistence of all of these features together is highly non-generic in the MSSM, and will serve as a powerful indicator of the presence of a sneutrino NLSP.

Our paper is organized as follows. In the next section, we give top down motivations for this scenario, discussing classes of mediation models in which a sneutrino NLSP may arise. In section III we summarize the details of the slepton/sneutrino spectrum, decays, and cosmology. In section IV we discuss generic event topologies and lepton accounting. (Readers mainly interested in collider phenomenology can start here.) We then perform a more detailed study of LHC signals in section V including estimates of the dominant backgrounds. Section VI finishes with some closing thoughts and ideas for further studies.

II. HOW TO GET A SNEUTRINO NLSP

A. Gauge Mediation

Giving up on a cosmological role for a light sneutrino, it finds a natural home in gauge mediation, where all would-be LSP’s are fated to decay into the gravitino. Indeed, a sneutrino NLSP readily arises is General Gauge Mediation [10]. GGM is defined as the class of UV completions of the MSSM which fulfill the following condition: in the limit where all gauge couplings are taken to zero, the theory decouples into the SUSY breaking sector and the MSSM with exact SUSY. This definition includes various perturbative messenger models (either of direct gauge mediation or including a separate messenger sector), as well as nonperturbative ones, where even the definition of the messenger field is obscure. In spite of the fact that this definition covers a very broad class of models with potentially very different collider signatures, all of these models possess some common features, like maintaining the sum rules $\text{Tr}[Y m^2] = \text{Tr}[(B - L)m^2] = 0$ for the sfermion soft masses (at the messenger scale), as well as parametrically suppressed $A$-terms.

GGM can be fully parameterized by six independent parameters at the messenger scale (not including the Higgs sector\textsuperscript{2} and the value of the messenger scale itself). One can think

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\textsuperscript{2} One needs an additional mechanism (which might not fit the definitions of GGM) in order to produce reliable $\mu$ and $B\mu$ terms. Such mechanisms usually significantly modify the soft masses of the Higgses from the GGM value (see e.g. [11, 12]). Therefore, in exploring the parameter space of GGM one should...
about this parametrization as follows: each gauge group of the standard model (SM) has some contribution to its gaugino and an independent contribution to the scalars charged under that group. We can parameterize the soft masses as

\[ M_r = g_r^2 M B_r, \quad m_f^2 = \sum_{r=1}^{3} g_r^4 C_2(f, r) M^2 A_r. \]  

(1)

In these formulas \( r \) runs over the three gauge groups of the SM. \( B_r \) are three complex numbers, and \( A_r \) are three real numbers. The \( g_r \) are the gauge couplings, and \( C_2(f, r) \) denotes the quadratic Casimir of \( f \) with respect to the gauge group \( r \). \( M \) is an overall soft mass scale.

The GGM framework admits a large variety of different spectra, far beyond that of minimal GMSB models. Not all of these spectra are fully understood in terms of collider signatures and experimental constraints. For example, the signatures of the promptly decaying neutralino NLSP at the Tevatron have been only recently studied in full generality in [13]. The chargino, which can also be the NLSP in a narrow region of GGM parameter space, has also been neglected for a long time and was first seriously considered only recently [14].

Obtaining sneutrino as the NLSP was found to be straightforward in [15, 16], even with restrictions on the GGM parameters. For example, in order to ensure that the LH slepton doublet is lighter than the RH slepton, it is adequate simply to demand\(^3\)

\[ A_2 \approx \frac{3}{5} \frac{g_1^4}{g_2^4} A_1 \simeq (0.2) A_1. \]  

(2)

The gauginos can subsequently be made heavier than the LH slepton completely independently by adjusting the \( B_r \), and the squarks can easily be made heavier as well.

Realizing this situation with perturbative models is also possible, though not quite so trivial. Using the GGM notation, the \( B_s \) are now related to the \( A_s \). Specifically, in order to make the wino arbitrarily heavy with respect to the LH slepton in models with purely \( F \)-term SUSY-breaking masses for the messengers, we would need arbitrarily large messenger

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\(^3\) Note that this is only a rough upper bound on \( A_2 \), since it does not account for radiative corrections or left/right mixing effects. In particular, near the boundary, stau mixing effects can become large, and \( \tilde{\tau}_1 \) may become the NLSP.
Dynkin index. However, perturbative gauge unification is spoiled unless the Dynkin is $\lesssim 5$, or the messenger scale is made very high. Taking the former constraint, the best we can do is to make the wino a little less than twice as heavy. At the same time, we must have a large mass for the RH slepton (which automatically also translates into a large mass for the bino), and this also feeds into the LH slepton via $A_1$, decreasing the gap with the wino. Without pushing to large Dynkin, the best we can manage is a rather squashed spectrum of sleptons and electroweak gauginos at the messenger scale, and mixing effects and radiative corrections can easily reorder it.

A simple model that manages to produce an acceptable spectrum contains two identical copies of $10 + \overline{10}$, with independent supersymmetric and supersymmetry-breaking masses for each of the SM irreducible representations. From the perspective of the electroweak gauginos and sleptons, the $Q$-like $((3, 2)_{1/6} + cc)$ messenger fields act as an approximately pure source of $A_2$ and $B_2$, and the $U$-like $((3, 1)_{-2/3} + cc)$ and $E$-like $((1, 1)_1 + cc)$ fields act as independently tunable sources of $A_1$ and $B_1$. The LH slepton is lightest by a comfortable margin when we choose parameters such that $B_1$ is $2 \sim 3$ times larger than $B_2$.

More generally, we can consider perturbative models with $D$-term contributions from a hidden gauge sector under which the messengers are charged. This was suggested in [18] as a way to fully realize GGM without resorting to strong coupling. In the case at hand, it allows us to independently decrease the LH slepton mass with respect to the wino mass without requiring arbitrarily large Dynkin index.

Clearly, then, a sneutrino NLSP in gauge mediation would point to a highly non-minimal, possibly nonperturbative messenger sector. Of course, even if the sneutrino NLSP is actually established at the LHC, determining whether the spectrum is due to non-minimal gauge mediation will be quite difficult, since even a prompt decay of the sneutrino is completely invisible. Still, there will be various clues encoded in the spectrum, namely the sum rules

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4 The messenger Dynkin sets upper bounds on the mass ratios between the gauginos and the sfermions. Indeed, it is straightforward to engineer models that reduce these ratios, but we know of no examples of the opposite effect.

5 This can easily be accomplished by coupling in multiple singlet fields which feel SUSY breaking, assuming the couplings are not $SU(5)$ symmetric. However, since the Dynkin index here is 6, the messenger scale must be $\mathcal{O}(1000)$ TeV or larger to permit perturbative gauge coupling unification. In a more complete analysis, one also needs to worry about threshold corrections from the explicit global $SU(5)$-breaking in the messenger spectrum.
above, near flavor-universality (and small $A$-terms), and perhaps even the apparent high-
scale non-unification of gaugino masses.

B. Other Scenarios

Obtaining the sneutrino at the bottom of the superparticle spectrum is also possible with
other mediation mechanisms, such as gravity mediation or gaugino mediation [19, 20].

One way to accomplish this [21] (see also [22, 23]) is to invoke highly non-universal
Higgs masses (NUHM) at the input scale. This leads to large hypercharge $D$-term loop
contributions in the renormalization group equations, what is usually called the “$S$-term”.
It is defined as

$$S \equiv \text{Tr} \left[ Y m^2 \right],$$

where the trace runs over all soft scalar masses of the MSSM, including the Higgses. It
contributes to the running of the superpartners as

$$\Delta \left( \frac{dm^2}{d \ln \mu} \right) = \frac{1}{8\pi^2} \left( \frac{3}{5} g_1^2 Y \right) S .$$

In parameterizations of high-scale mediation with universal soft masses, this term vanishes at
the scale where the soft masses are produced. However, by taking the Higgs mass parameters
independent of the sfermions, and making the down-type mass much larger than the up-type,
the $S$-term can push the RH slepton mass higher than the LH slepton mass.

Since the down-type Higgs mass is very large in these scenarios, the contributions to
the running of the third generation masses is significant. In particular, the third-generation
slepton doublet can be appreciably lighter than the other two, at the level of 10’s of GeV. This
has led to several discussions [24–27] that emphasize signals with taus. We will not pursue
this approach here, but note that large flavor non-degeneracies within the sneutrinos can
lead to additional variations on the more general signals that we will explore in section IV.
We defer investigation of these to [9].

Another, simple way to obtain a sneutrino NLSP in gravity mediation is by using inde-
pendent (but flavor-universal) masses-squared for the 5 and 10 representations of $SU(5)$.

\footnote{In spite of the fact that the gravitino is not a guaranteed LSP candidate in these scenarios, it is a logical
possibility which we further consider.}
The RH slepton can be made arbitrarily heavier than the LH slepton in this way, but in order to end up with the LH slepton lighter than the bino, we should go to negative $m_5^2$. The tachyonic masses for the LH slepton and RH down squark will run positive in the IR, provided they are not too large in magnitude, and they should not pose any phenomenological difficulties.\footnote{Universal negative masses-squared were considered in \cite{28}.} Since the Higgs soft masses are not necessarily very large, flavor non-universal contributions to the sleptons will typically be smaller. These spectra should fall under our analysis here.

Physics beyond the MSSM could also play a role. For example, the LH slepton can be rendered light via renormalization group running induced by couplings to right-handed neutrinos, as recently proposed in \cite{29}. Even though this paper did not consider spectra with sneutrino NLSP and gravitino LSP, it is likely possible to achieve with the same kind of setup. Since the physical mass spectrum here depends on new, unknown Yukawa couplings, flavor violation effects may be arbitrary. This is an interesting possibility, but falls outside the scope of our present work.

In this paper, we will consider spectra that are relatively flavor-universal. We have noted that a gravity mediation scenario with negative $m_5^2$ may fall into this class, but most of the alternatives involve some non-negligible degree of flavor violation, for example leading to tau-enriched signatures. In particular, the discussions of \cite{24,27,29} are essentially independent of our own observations below regarding flavor-universal multi-lepton signals.

III. GENERAL PROPERTIES OF MODELS WITH A SNEUTRINO NLSP

In this section, we discuss in more detail the generic features of the LH slepton and sneutrino states. We first work out the fine-structure of the mass spectrum, then discuss decays of the charged sleptons, and finally consider the role of the sneutrino NLSP in cosmology.

A. Slepton and Sneutrino Mass Spectrum

Before electroweak symmetry breaking, all three flavors of sneutrino are precisely degenerate with their charged partners. The measured difference between mass eigenstates
is dictated by electroweak $D$-terms and by the mixing between the left- and right-handed sleptons.

The $D$-terms act to make the charged sleptons heavier than the sneutrinos for $\tan\beta > 1$:

$$m_{\tilde{\tau}^+_{L}} - m_{\tilde{\nu}} = \frac{m_W^2 (-\cos(2\beta))}{m_{\tilde{\tau}^+_{L}} + m_{\tilde{\nu}}} \approx \frac{m_W^2 \sin^2\beta}{m_{\tilde{\tau}^+_{L}} + m_{\tilde{\nu}}},$$

(5)

where in the last term we have displayed the large $\tan\beta$ limit, which becomes accurate to better than $O(10\%)$ for $\tan\beta \gtrsim 3$. The splitting is inversely proportional to the average doublet mass, and is always less than $m_W$. For example, for masses near 200 GeV, the splitting is about 16 GeV or smaller.

In the third generation, left/right mixing effects might become important. The mass-squared matrix of the $\tilde{\tau}$s is

$$\begin{pmatrix}
  m_{\tilde{\tau}_{L}}^2 + \Delta_L & -\mu y_{\tau} \sin\beta + v A_{\tau}^* \cos\beta \\
  -\mu^* y_{\tau} \sin\beta + v A_{\tau} \cos\beta & m_{\tilde{\tau}_{R}}^2 + \Delta_R
\end{pmatrix},$$

(6)

where we have represented the electroweak $D$-term contributions to LH and RH sleptons as $\Delta_L$ and $\Delta_R$, respectively. If we neglect $A$-terms, and if the the $\mu$/Yukawa terms are not too large compared to the mass-squared difference, the (mostly) left-handed stau is shifted down by approximately

$$\frac{-\mu^2 v^2 y_{\tau}^2 \sin^2\beta}{m_{\tilde{\tau}_{R}}^2 - m_{\tilde{\tau}_{L}}^2}.$$  

(7)

(The $D$-term contributions have been neglected in the denominator, but they are small, roughly $(20 \text{ GeV})^2$.) This can potentially make $\tilde{\tau}_1$ the NLSP, if the mass correction from mixing is larger than the electroweak doublet splitting above. Clearly then, in any viable sneutrino NLSP scenario, we will require

$$\frac{\mu^2 v^2 y_{\tau}^2}{m_{\tilde{\tau}_{R}}^2 - m_{\tilde{\tau}_{L}}^2} \lesssim m_W^2.$$  

(8)

In general then, spectra with sneutrino NLSP can have quite detailed fine-structure for the lowest-lying states. Here, we will be interested in cases with approximate flavor degeneracy between the three slepton doublets, which carries over to the three flavors of NLSP.

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8 The LH stau doublet also receives flavor-nonuniversal mass corrections at loop level. These tend to push the third generation lighter, making the tau-sneutrino lightest. If these corrections are large, such as in high-scale scenarios with large Higgs soft masses, then $\tilde{\tau}_L$ can be lighter than the sneutrinos of the first two generations, even before left/right mixing is taken into account. We will not consider such scenarios here, but see [1].
sneutrinos. The stau-sneutrino will be the true NLSP, but the splitting with the other sneutrinos will not be large enough to generate any visible activity. Stau mixing will always push the $\tilde{\tau}_1$ lighter than the first- and second-generation $\tilde{l}_L^+$, but as long as it stays heavier than the sneutrinos, the modifications to the phenomenology we consider here are minor.

### B. Decays

In equation (5), we saw that in general the mass splitting between the sneutrino and its charged slepton partner is always less than $m_W$. If all of the charginos and neutralinos are heavier, then the charged slepton decays will be dominated by $W^*$ emission: $\tilde{l} \to \tilde{\nu} f f'$ (see Fig. 1).\(^9\) (Subsequently, $\tilde{l}$ will always refer to $\tilde{l}_L$, so we drop the subscript.) As long as $m_{\tilde{l}^+_L} - m_{\tilde{\nu}} \gtrsim \text{few GeV}$ (which for even modest $\tan \beta$ is almost always true), the branching fractions into different species of quarks and leptons will be very similar to that of on-shell $W$s. In particular, it will produce $e$ or $\mu$ approximately 22% of the time. It can also produce leptons from secondary $\tau$ decays, but the vast majority of the other decay modes will contain low-multiplicity jets. These will be quite difficult to cleanly identify, and we will not explore the possibility of using them in our searches.

Seeing the products of the $e$ and $\mu$ decay modes could in principle be complicated by the fact that the slepton/sneutrino mass splitting can become quite small, and that it is three-

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\(^9\) Virtual gauginos will also contribute to the decays, opening up additional modes, and interfering with some of the $W^*$ modes in a flavor-dependent way. Practically, these tend to be much less important if the gauginos are well above $m_W$. 

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body. In the example given in the previous subsection, of a 200 GeV doublet split by 16 GeV, the average lepton momentum in the slepton rest frame is about 8 GeV. This approaches the threshold for good quality lepton identification in the LHC experiments. So a fraction of the leptons, from the softer region of the emission spectrum, may be unobservable. Since the hardness of the emitted leptons scales inversely with the doublet mass, heavier sleptons will yield softer leptons, possibly leading to $O(1)$ loss of signal. This may be partially compensated for in strong SUSY production, in which the sleptons may be produced with substantial boost from decay chains initiated by much heavier squarks and gluinos.

Since for cosmological reasons, we work with models where the sneutrino is the NLSP and the gravitino the LSP, we should also be mindful of the possibility that the charged LH slepton can decay directly to the gravitino and a charged lepton, much like a RH slepton NLSP. Though suppressed by some mass scale significantly larger than $m_{\tilde{W}}$, this decay is two-body, and typically has much more phase space than the $\tilde{\nu}l\tilde{\nu}$ mode.

Assuming $m_{3/2} \ll m_{\tilde{l}}$, the decay width into gravitino and lepton is given by

$$\Gamma(\tilde{l} \to \tilde{G}l) \simeq \frac{m_{\tilde{l}}}{16\pi F^2},$$

where $\sqrt{F}$ is the fundamental SUSY-breaking scale. The decay width into $\tilde{\nu}l\tilde{\nu}$ by $W^*$ emission goes as

$$\Gamma(\tilde{l} \to \tilde{\nu}l\tilde{\nu}) \simeq \frac{\alpha^2}{30\pi} \frac{(m_{\tilde{l}} - m_{\tilde{\nu}})^5}{m_{\tilde{W}}^4} \simeq \frac{\alpha^2 |\cos(2\beta)|^5 m_{\tilde{W}}^6}{2^6 \cdot 15\pi} \frac{m_{\tilde{l}}^5}{m_{\tilde{W}}^5},$$

where have used equation (5) and taken the small splitting limit. The two-body decays become competitive if

$$\sqrt{F} \lesssim \left( \frac{60}{\alpha_2^2 |\cos(2\beta)|^5} \frac{m_{\tilde{l}}^{10}}{m_{\tilde{W}}^6} \right)^{1/4} \simeq (2 \text{ TeV}) \frac{1}{|\cos(2\beta)|^5} \left( \frac{m_{\tilde{l}}}{100 \text{ GeV}} \right)^{5/2}. \quad (11)$$

For modest values of $m_{\tilde{l}}$, such a small value of $\sqrt{F}$ is difficult to obtain in known models. For bigger values of $m_{\tilde{l}}$, the two-body decays will be relevant for a small part of the viable parameter space. In subsequent sections, we will simply assume that the SUSY-breaking scale is not so small, and that two-body decays are subdominant. However, cases with significant two-body contributions would also be interesting to study.\(\text{\textsuperscript{10}}\)

\(\text{\textsuperscript{10}}\) If two-body dominates, then the phenomenology would look very similar to RH slepton NLSP, but with
C. Cosmology

A sneutrino NLSP decays mostly invisibly, into neutrino and gravitino, and its would-be relic density becomes attenuated by $m_{3/2}/m_{\tilde{\nu}}$. For most choices of parameters, it decays before matter domination. Therefore the neutrinos generated in its decay would presently constitute a subdominant non-thermal component of the cosmic neutrino background. In the cases where the gravitino is heavy enough to deposit a visible amount of kinetic energy in terrestrial nuclear recoil experiments, the gravitino-on-nucleon cross section is suppressed to a point well below present bounds.

The possibility that the gravitino produced in the decay is in fact dark matter, or some component of it, has been considered in a number of papers (see, for example, [30, 31]). Since we are mostly interested in collider signals, we will not explicitly consider this.

Despite the elusive nature of the sneutrino’s main decay products, rare decays involving on-shell or off-shell gauge bosons do produce visible particles. If the lifetime of the sneutrino is longer than a few seconds, these can upset the light element abundance of nucleosynthesis. This possibility was considered in detail in [32]. For sneutrinos lighter than about 300 GeV, and/or gravitinos lighter than about 4 GeV, there is no constraint. In particular, low-scale mediation scenarios like gauge mediation are automatically cosmologically safe.

IV. SUSY CASCADES WITH A SNEUTRINO NLSP

When all decay chains end in the LH slepton doublet, there can be significant modifications compared to more standard MSSM spectra. In this section, we will discuss these features and categorize promising decay topologies for searches at the LHC.

The simplest SUSY events available at the LHC are direct pair production of the sneutrino and/or its charged partner, accompanied by a decays through $W^*$ in the latter case (Fig. 1).

In a hadron collider environment, none of these options is particularly easy to find. Sneutrino pair production is completely invisible, and could only be detected in principle through ISR, essentially impossible at the LHC. Including the charged slepton leads to relatively soft

modified lepton counting. Instead of every event containing at least two hard leptons (and/or taus), each decay chain would now have a $O(50\%)$ chance of ending via $\tilde{\nu} \rightarrow \tilde{G} \nu$. In a scenario with mixed two-body and three-body decay events, the former will introduce an additional population of opposite-sign same-flavor (OSSF) leptons from charged slepton production and decay.
leptons and/or jets with very little missing energy. It will likely be swamped by physics backgrounds and fakes, even in the dileptonic mode.

We are therefore led to consider more complicated processes, where the sneutrino is the final particle emitted in cascades initiated by gauginos or squarks/gluinos. As usual, the most striking situation is $O(\text{TeV})$ super-QCD (SQCD) production, and we choose to focus on this case. Electroweak (EW) production of gauginos may also be visible, particularly in trilepton (or higher) channels. These become particularly important when the squarks and gluinos are much heavier than a TeV, and therefore difficult to produce. We do not study these explicitly, but the general observations below for the structure of trilepton signals in SQCD production should carry over essentially unchanged.

Before we proceed, let us summarize our main assumptions, and describe more carefully the types of spectra we will analyze:

- The RH sleptons are heavier than the (mostly-)bino,

$$m(\tilde{e}_R) > m(\tilde{B}).$$

This is sufficient to ensure that the RH slepton is bypassed in the vast majority of the decay chains. We will consider spectra with this inequality reversed in [9].

- Approximate flavor degeneracy. In particular, the fine structure of the three LH slepton doublets is dominated by the $D$-term splitting in equation (5). The sneutrinos are mass-degenerate for all practical purposes. The mostly-LH stau may be somewhat lighter than the other charged sleptons, but still heavier than the sneutrinos.

- All other superparticles are heavier than the charged LH slepton states.

- $O(\text{TeV})$ colored superpartners, sitting above the EW gauginos.

- Modest gaugino-Higgsino mixing.

- Negligible $A$-terms at the mediation scale.

11 Squarks near 1 TeV are actually favored to achieve $m_H > 114$ GeV (via loop corrections) in the MSSM, in the absence of large $A$-terms and with near flavor degeneracy. Of course, it is not difficult to circumvent this in extensions of the MSSM [32], for example [33, 34]. Similar issues were earlier discussed in [36, 37].
In the following subsections, we will explore the signals of this class of scenarios in more detail, as well as the difficulty of replicating them in alternative MSSM spectra. The discussion is at the conceptual level, without worrying about many of the complications of the hadron collider environment. We will perform a more realistic analysis illustrating these ideas in simulation in section.

### A. Lepton Counting

Consider, as a first stage, simple counting of the leptonic events including flavor/sign correlation between the leptons in dileptonic events. We will see that this lepton accounting is quite distinctive with a sneutrino NLSP.

Starting from squark/gluino production, each decay chain must proceed down to the slepton doublet through charginos and neutralinos. Since we will be assuming that the colored superparticles are heaviest, these will always be treated as on-shell. However, this point is not crucial for many of our observations.

We also neglect decay chains containing (mostly-)Higgsinos. These will be relevant for chains initiated by stops and sbottoms, but they will not typically serve as more than a correction to our signals.12

We therefore concentrate on the decays of charginos and neutralinos that are mostly wino and bino. We illustrate the decay chains in Fig.2. Up to possible phase space suppressions, and coupling shifts due to gaugino mixing, any EW gaugino decay has a 50% probability of producing a charged lepton in the first stage of the decay chain. Since the decays are flavor-blind, 1/3 of these leptons will be taus. At first pass we will treat these as “hadrons,” considering only the prompt production of electrons and muons. This still leaves 1/3 of the gaugino decays, whether chargino or neutralino, going into one of these highly visible lepton modes. This leads to a significant chance for each SUSY event to contain one or two hard, isolated leptons. Specifically, the ratio of dilepton:monolepton:no-lepton would be roughly 1:4:4.

If this had been the only source of the isolated leptons, then the dilepton signal would have

12 Spectra with strongly mixed charginos and neutralinos are an obvious exception to this. Also, in relatively unmixed cases with very light Higgsinos, they may contribute to the EW gaugino decay chains, via Higgs or electroweak boson emission.
FIG. 2: Possible decay modes of gauginos, with $W^*$ decaying leptonically. Notice the sign and flavor flow on the last diagram, with two charged leptons in a single decay chain. While the leptons’ signs are correlated, their flavors are not.

been completely charge and flavor uncorrelated, since each lepton is produced in a different chain.\textsuperscript{13} However, we also have leptons from the charged slepton’s decay via $W^*$. Although these leptons tend to be softer, due to the approximate slepton-sneutrino degeneracy, they are still often visible. To some extent, these add to the monoleptonic signal, but their effects at higher multiplicity are much more interesting.

In the dileptonic events, we now have contributions where both leptons come from a single neutralino decay chain (either bino or neutral wino), as in the lower-right diagram of Fig. 2. Since the probability of the first decay to produce an electron or muon (plus selectron or smuon) is $1/3$, and the probability of the second to do the same is approximately $2/9$, we get a roughly 7% chance to get two leptons in a neutralino decay. These leptons are necessarily opposite-sign (OS), but they are flavor-uncorrelated. This is to be contrasted with the completely sign/flavor-uncorrelated dileptons discussed above.

\textsuperscript{13} Sign correlation across the event can occur to some extent. For example, we can have LH squark-antisquark pair production followed by decays into charged winos on both sides, each subsequently decaying into charged leptons. This leads to opposite-sign leptons. Similarly, squark-squark production (from valence quarks annihilating via gluino exchange) may have a bias towards same-sign leptons. Practically, neither of these tends to lead to an overwhelming charge bias, when all production and decay modes are taken into account.
Since this signal can be produced from neutralino decays, but not from chargino decays, its size depends on their relative production rates. For example, in the case of events that contain two binos, these OS dileptons would account for roughly half of all dileptonic events. Pure wino production would have a weaker signal, as there is only a $1/3$ chance for a given side to produce $\tilde{W}^0$. In such a case, the excess OS leptons account for about 15% of the dileptonic events. In both cases, the dilepton channels account for almost 20% of all events, with monolepton and no-lepton each accounting for $35 \sim 45\%$.

We can further subdivide the dileptonic modes in the usual way, using the relative sign/flavor of the two leptons. They can be either opposite-sign opposite-flavor (OSOF), opposite-sign same-flavor (OSSF), same-sign opposite flavor (SSOF), or same-sign same flavor (SSSF). For the signals discussed above, we get flavor-universal ratios of 1:1 for OSOF:OSSF and SSOF:SSSF. But given the presence of our OS lepton production from neutralino decay followed by slepton decay, there will be an excess of OSOF and OSSF compared to SSOF and SSSF. The numbers above suggest that this excess will be $O(0.1 \sim 1)$.

In addition, there will be very distinctive trilepton modes, where one side of the event produces OS dileptons in neutralino decay, and the other side produces a single lepton in either chargino or neutralino decay. The rates for these processes are only about 2 times smaller than the OS dilepton excess. We will discuss these in more detail in subsection [IV.C], but at this point we can already see that the three leptons will be completely flavor-uncorrelated, and that there will be no events where all three leptons have the same sign.

There will even be a population of 4-lepton events, when both chains produce two OS leptons. This tends to be smaller than the trileptons by about an order of magnitude. We will not carefully investigate these events, but they will serve as further confirmation if they are observable.

To summarize, we expect the following pattern of multilepton events when the sneutrino is the (N)LSP:

- 35 $\sim$ 45% of all SUSY events will have no leptons, another 35 $\sim$ 45% will contain one lepton, and close to 20% will be dileptonic.

- On top of a general sign/flavor-uncorrelated signal from leptons produced in independent chains, the dileptonic channel will contain a flavor-uncorrelated excess of OS events. The relative size of this excess depends on the relative rates of gauginos pro-
FIG. 3: The diagram responsible for the \( \tilde{\chi}^0 \) decay down to \( \tilde{\chi}^0 \) via an intermediate (possibly off-shell) slepton, which occurs in more conventional spectra. The leptons are correlated in both charge and flavor, falling into the OSSF category.

![Diagram](image1)

FIG. 4: Schematic illustration of the standard SUSY dilepton flavor subtraction. The left panel shows the OSSF (magenta, solid) and OSOF (blue, dot-dash) dilepton invariant mass distributions. To extract the correlated contribution to OSSF, we subtract the OSOF shape. The right panel shows the result of the subtraction.

produced, but it will account for between 15% and 50% of the entire dilepton sample.

- Trilepton events will be present, with numbers roughly half as large as the correlated OS excess (OS minus SS signal).

- 4-lepton events may also be observable, though they will have much smaller rates.

We emphasize that these are just rough estimates. In particular, phase space and mixing of gaugino couplings can in principle modify these numbers at the \( O(1) \) level.
B. Opposite-Sign Dilepton Excess

A standard signal of many SUSY spectra is an excess of OSSF dileptons, from the neutralino chain depicted in Fig. 3. This is generally accompanied by flavor-uncorrelated backgrounds, from both the SM and from SUSY. If we plot the dilepton invariant mass distributions from both the OSOF and OSSF channels, we see purely uncorrelated lepton pairs for the former, and a combination of uncorrelated and correlated leptons for the latter (left panel Fig. 4). In order to isolate the correlated contribution, one can perform a flavor subtraction, OSSF minus OSOF (right panel Fig. 4). This reveals a dilepton mass distribution which contains information about the mass splittings between the neutralinos and the slepton. For example, when the slepton is on shell, we get the characteristic ramp and edge shape.

With the sneutrino NLSP spectra, we find ourselves in a very analogous situation. As discussed above, opposite-sign uncorrelated-flavor lepton pairs are produced in the decays of neutralinos into charged sleptons, followed by decay down to the sneutrino (bottom-right panel of Fig. 2). These decays will produce their own distinctive dilepton invariant mass distribution (discussed in more detail below), now encoded in equal excesses in the OSOF and OSSF channels. Immediately, we can see that the above subtraction scheme...
FIG. 6: The OS dilepton invariant mass distribution from the sequence $\tilde{\chi}^0 \rightarrow l^{-}_i \tilde{l}^+_i \rightarrow l^{-}_i (l^+_j \nu_j \tilde{\nu}^*_i )$, with spectrum $m_{\tilde{\chi}^0} = 362$ GeV, $m_{\tilde{l}} = 232$ GeV, $m_{\tilde{\nu}} = 218$ GeV. The black line shows the distribution from flat phase space. The red line shows the distribution incorporating matrix elements. The histogram shows a distribution obtained using BRIDGE. 

will completely miss this signal. In order to find it, one should perform a subtraction not in flavor, but in sign.\textsuperscript{14} This is illustrated in Fig. 5. In order to further test flavor universality, the subtraction can be performed in individual opposite-flavor and same-flavor categories (OSOF minus SSOF, and OSSF minus SSSF). Subsequently, we will leave this option implicit, and simply refer to OS and SS categories.

Two important qualifications to this procedure are in order. First, it is possible that the SUSY production will have sign correlations, for example if it is biased towards squark-antisquark pairs from s-channel gluons. In such a case, the uncorrelated OS and SS distributions may have different normalizations. However, they will still have the same shape. The OS excess could then still be revealed with a weighted subtraction, such that the subtracted shape is left with no high-mass tail. Second, the SM backgrounds (mainly $t\bar{t}$) are dominantly OS. Indeed, the discovery of the SS signal will be a cleaner first indication that there is new physics at play. In the standard flavor-subtraction, these backgrounds cancel out. In our case, they do not. Interpretation of the SS-subtracted OS excess as additional new physics will therefore require greater care. Nonetheless, as we will show in section \textbf{V}, the

\textsuperscript{14} A similar subtraction has recently been advocated in \cite{38}, in studying scenarios with mostly right-handed sneutrino LSP in the MRSSM \cite{39}. However, the framework there is genuinely flavor-violating, and incorporates different analysis tools.
backgrounds can be brought to a manageable level, such that the signal becomes dominant with reasonable spectra.

In addition to a somewhat unconventional distribution between sign/flavor bins, the shape of the OS excess has its own unique features. We can first observe that instead of a sequence of two 2-body decays or one 3-body decay, we have a 2-body decay followed by a 3-body decay. In fact, this possibility has already been discussed in the context of models with mostly right-handed sneutrinos as the (unqualified) LSP \[40\]. There it was pointed out that the dilepton mass distribution has a shape distinct from both of the ordinary two options. We display this shape for a sample spectrum, with and without spin effects in the slepton decay, in Fig. 6. (We also include a distribution obtained with the program BRIDGE \[41\], which we further utilize in the analysis of section \[V\].)

As usual, this shape contains information on the masses (and even the spins) of the particles participating in the decays. The endpoint is given by the same kind of expression which describes the endpoint of the \(\tilde{\chi}_0^2 \to \tilde{l} \to \tilde{\chi}_1^0\) sequence with on-shell slepton:

\[
m_{\text{max}} = \sqrt{\frac{(m_{\tilde{\chi}_0^2}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\nu}}^2)}{m_{\tilde{l}}^2}} \simeq \sqrt{2(m_{\tilde{\chi}_0^2}^2 - m_{\tilde{l}}^2)\frac{m_{\tilde{l}} - m_{\tilde{\nu}}}{m_{\tilde{l}}}}. \quad (13)
\]

We also note that in the small-splitting limit, the entire distribution achieves a universal shape, described by a ninth-degree polynomial. For details, see appendix A. The peak, which may be much easier to measure in practice than the endpoint, occurs near \((0.48)m_{\text{max}}\).

Several other aspects of the OS dilepton excess are worth noting:

- The distribution may be bimodal, corresponding to the two subchains \(\tilde{\chi}_2^0 \to \tilde{l} \to \tilde{\nu}\) and \(\tilde{\chi}_1^0 \to \tilde{l} \to \tilde{\nu}\). If the two neutralinos have similar masses, then they may be difficult to disentangle.

- While the presence of the completely sign- and flavor-uncorrelated dilepton events acts like a background here, its presence is also a crucial point of verification of the sneutrino NLSP interpretation. As per the accounting in the previous subsection, the total number of uncorrelated dilepton events will be \(\mathcal{O}(1 \sim 10)\) larger than the observed OS excess.

- As we have already mentioned, the slepton/sneutrino mass difference scales inversely with the average doublet mass, and can be relatively small compared to the superpartner mass scale. Consequently, the lepton produced in the slepton decay will not...
necessarily have much available energy, and it must share this with the neutrino and (to a much lesser extent) the sneutrino. This can complicate the clean identification of the lepton, which on average acquires an energy of approximately \((m_{\tilde{l}} - m_{\tilde{\nu}})/2\) in the slepton rest frame. (For example, for a 200 GeV doublet, the average energy is about 8 GeV.) With strict identification requirements to reject fakes, and tight isolation cuts to reject heavy flavor decays, \(O(1)\) of these leptons may be unusable. We will demonstrate that a significant fraction can still be used in realistic cases in section V.

C. Trileptons

Whenever one side of the event produces an OS dilepton pair, the other side has \(O(1/3)\) chance of also producing a lepton via gaugino decay. This leads to a roughly 2:1 ratio between rates for correlated OS dilepton events and very distinctive trilepton events, which have smaller SM backgrounds. If the OS excess is generated with high enough statistics to be clearly observable, the trilepton events will be observable as well. Indeed, the presence of these trilepton events may very well be established before the OS minus SS subtraction is possible.

Beyond simple counting, it should also be possible to extract the correlated dilepton mass distribution (Fig. [4]) from these events, leading to a powerful confirmation of the overall picture. However, there is an immediate combinatoric problem to be overcome. The only sign/flavor structure between these three leptons is that they cannot all have the same sign. In general, in every event we will be able to find two possible OS dilepton pairings, only one of which is the correct one. This is to be contrasted with the analogous production of trileptons in more standard SUSY spectra, where we are always guaranteed an OSSF pair. There we can focus on events where this pair is generated with a lepton of the opposite flavor.

For our case, we propose a simple strategy which breaks the degeneracy and directly extracts the correct distribution to good approximation. The lepton emitted in the slepton decay will tend to be the softest lepton in the event. Assume that this is indeed the case. Focus on the subsample of events where only one of the hardest two leptons can form an OS pair with this soft lepton. (Equivalently, the two hardest leptons should be OS with respect to each other.) When we form the invariant mass distribution from this (half-sized)
subsample, we should have a much higher probability of having guessed correctly, and the mass distribution should reflect this. We find that this technique works well in practice, and demonstrate its application in section V.

The trilepton signal could also be useful for discovery via electroweak production of gaugino pairs. As usual, the high lepton multiplicity can make the events distinctive enough that SM backgrounds can be controlled, even though the accompanying jet activity and missing energy are not necessarily very large. We will not explicitly investigate this discovery channel here, but note that the observations of this section clearly still apply. In particular, the signal can immediately be discriminated from typical trilepton SUSY production by the complete lack of flavor correlations.

It is possible that the Tevatron is already capable of placing interesting limits on sneutrino NLSP spectra in EW production. We save investigation of this for future work.

D. Jet-Lepton Invariant Mass

As in more traditional searches, we can also attempt to construct kinematic observables from the jets produced in the cascades. In particular, the sequence \( \tilde{q} \rightarrow q\tilde{\chi} \rightarrow ql(\tilde{l}/\tilde{\nu}) \) results in a jet and a lepton, from which we can construct an invariant mass distribution. Since we assume that the gaugino is on-shell, this distribution has the same ramp-and-edge shape that characterizes the dilepton mass distribution in \( \tilde{\chi}_2^0 \rightarrow l^+\tilde{l}^- \rightarrow l^+l^-\tilde{\chi}_1^0 \) (right panel Fig. 4).\(^{15}\) Extraction of such a shape would help further confirm the origin of the leptons. It would also provide information on the squark/gaugino mass splittings since the edge is predicted to occur as in equation (13) with appropriate replacements.

Of course, reality is not so straightforward. Even assuming high quality jet measurements, we are always left with combinatoric ambiguities since each side of the event will produce jets. Still, even incorporating multiple pairing possibilities into the construction of the mass distribution (or simply guessing at random), nontrivial edge features will remain. With high enough statistics, we may be able to cleanly identify these edges, recovering some kinematic information and achieving greater confidence that we are seeing leptons produced.

\(^{15}\) Because the intermediate particle in the decay chain is now spin-1/2, there will be spin effects modifying the distributions from flat phase space. However, these average out when we sum over quark and lepton charges.\(^{42}\)
in two-body gaugino decays.\textsuperscript{16}

In events with gluino decays, these edges can be washed out, or disappear entirely. A
heavier gluino decaying via an on-shell squark injects an extra hard jet into the event, further
complicating the combinatorics. A lighter gluino decaying via off-shell squark effectively
destroys the ramp-and-edge structure. In cases where gluino production dominates, there
may therefore be no edge-like features in the jet-lepton invariant mass distribution.

It should also be noted that we may accidentally use a lepton produced in slepton decay,
versus gaugino decay, in the jet-lepton mass. However, this is not a major issue. Monolep-
tonic events are already dominated by leptons produced in gaugino decay (by a factor of
3 \sim 6), and can be further purified by demanding harder leptons. In multilepton events, we
usually make a correct choice by taking the hardest lepton.

\textbf{E. How Unique are These Signals?}

Will these signals be enough to confidently infer that the decay chains are ending in
sleptons/sneutrinos? In order to address this question, let us consider how leptons are
produced in alternative scenarios within the MSSM.

SUSY cascades primarily generate leptons in three ways: decays of gauginos into slep-
tons/sneutrinos, decays of sleptons/sneutrinos into gauginos, and decays of electroweak
gauge bosons emitted in transitions between charginos/neutralinos. Any of these parti-
cles could also be off-shell. In sneutrino NLSP spectra, a fourth option opens up, from the
decays $\tilde{l} \rightarrow \tilde{l} l \tilde{\nu}$ discussed in subsection III.B. This is a crucial component of our signal. But
when sneutrino is not at the bottom of the spectrum, these three-body decays are bypassed
in favor of the two-body decays $\tilde{l}^+ \rightarrow \tilde{\chi}^0 l^+$ or $\tilde{l}^+ \rightarrow \tilde{\chi}^0 \nu$.

The most commonly considered way to produce multiple leptons in the same chain is
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0$ via an intermediate slepton, as shown in Fig. 3. This leads to a very distinctive
excess in the OSSF dilepton channel, typically constituting an $\mathcal{O}(1)$ fraction of all dilepton
production. Such an excess will not be present with our sneutrino NLSP unless we also
introduce the RH slepton into the cascades. (But this has its own set of novelties, which we
will discuss in \cite{9}.)

\textsuperscript{16} It was also suggested in \cite{40} that a kind of subtraction, analogous to what is done for dilepton distributions,
might be possible in order to remove the shape contribution from uncorrelated jet-lepton pairings.
This OSSF excess is a very generic signal whenever charged sleptons participate in the decay chains. But it can be hidden if there is an accidental mass degeneracy with one of the charginos/neutralinos, such that one of the emitted leptons becomes very difficult to find. Assuming this occurs, then we are left with uncorrelated production, where the leptons in dileptonic events always come from opposite chains. If the sleptons are rarely bypassed, this could lead to a similar dilepton:monolepton ratio.

Another way to get single leptons in each chain is through emission of $W^{(*)}$, from a $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0$ transition, or vice-versa. The branching fraction into electron and muon is 22%, which is not so different from our 33% branching fraction for gaugino decays into sleptons. The counting may therefore be different only at the $O(1)$ level, assuming the $W^{(*)}$ is produced in most decay chains.

While each of these two possibilities – slepton transitions with a near-degeneracy and $W^{(*)}$ emission – do not lead to correlated dileptons within a single chain, there may nonetheless be sign correlations across an event originating at production. (Again, domination by squark-antisquark production is a simple example.) The naive sign-subtraction procedure in the dilepton invariant mass distribution will leave over an OS excess, but, unlike the sneutrino NLSP case, this will have exactly the same shape as the SS distribution (up to SM backgrounds). In addition, if we only get one lepton produced in each of the two decay chains in an event, we will never get a trilepton excess. In order to get either a distinctive OS excess or trileptons, we generally need the possibility of two leptons being produced in the same chain.

To get multiple lepton emissions, we can string together these types of transitions. Indeed, a $W^*$ emission in association with slepton production or decay could closely mimic the pattern of our signal, particularly if there is a modest degeneracy analogous to the slepton/sneutrino mass splitting.

While these are indeed logical possibilities, they are clearly highly non-generic. Besides the requirement of strong accidental mass degeneracies to hide the OSSF signals whenever

17 An obvious way around this is to have large flavor violation in the slepton sector. This is clearly dangerous from the perspective of $\mu \rightarrow e\gamma$, so we assume flavor universality in our own analysis. But for some interesting ways to have large SUSY flavor violation while avoiding disagreement with low energy precision experiments, see [43, 44] and [39]. In order to fake our flavor-uncorrelated signal, this non-universality would need to be nearly maximal, but this possibility is excluded (see [45] for review).
sleptons contribute, at least three distinct mass levels of charginos/neutralinos must be participating in almost every decay chain. This might become possible when there is large mixing, or if the mostly-Higgsinos are much lighter than the mostly-gauginos. We will not investigate these alternatives in detail, since, in any case, there are too many variations to explore exhaustively. But these arguments do suggest that the pattern of leptons in spectra with a sneutrino NLSP is quite distinctive.

V. LHC SIMULATIONS

In this section we will use the tools developed in section IV in order to analyze two example spectra. We perform simulations including showering/hadronization, event reconstruction at particle level, and SM backgrounds. We do not attempt to incorporate a detector simulation or energy resolution effects. The purpose here is to demonstrate the plausibility of a real search at the LHC, given the presence of backgrounds and a jetty environment where leptons might be lost, or simply fall below the energy threshold of good quality reconstruction. This last point is particularly relevant for the leptons produced in slepton decay down to the sneutrino, which can be somewhat soft due to the small mass splitting.

In the following, we will assume that the LHC will ultimately reach its design energy of 14 TeV. We do not expect that a lower final operating energy will qualitatively change our conclusions. For example, at a 10 TeV LHC, the signal cross sections are reduced by a factor of about $3 \sim 4$.

A. Sample Spectra

There are many possible spectra with sneutrino NLSP that we might consider, but most of them lead to qualitatively similar phenomenology if we restrict ourselves to the assumptions outlined in section IV. In particular, the mass ordering between the wino and bino is not

| $\tilde{g}$GGM | $10^5$ | 350 | 370 | 1200 | 350 | 200 | 499 | 539 | 500 | -60000 | 60000 | 10 | + |
| $\tilde{g}$GGM | $10^5$ | 350 | 370 | 600 | 352 | 200 | 1500 | 1514 | 1500 | -60000 | 60000 | 10 | + |

TABLE I: Input parameters for the sample spectra in units of GeV (GeV$^2$ for the masses squared).
very important, as long as they are lighter than the squarks and gluinos. Other than very
detailed variations involving large gaugino-Higgsino mixings, or introduction of approximate
mass degeneracies, the main flexibility available to us is the mass of the LH slepton doublet
and the production of the gauginos in squark/gluino decays. The former controls the mass
splitting between the slepton and sneutrino, and hence the energy of the leptons produced in
slepton decays. The relative rates of bino versus wino production will control the size of our
OS dilepton excess and trilepton signal. Weaker signals occur if winos dominate, since fewer
neutralinos will be produced. In addition, the proportion of gauginos produced directly in
squark decays versus in gluino decays will determine the visibility of edge structures in the
jet-lepton invariant mass distribution.

We concentrate on two SUSY spectra with sneutrino NLSP within the framework of GGM
with arbitrary Higgs sector. The spectra have similar slepton and gaugino masses, but the
ordering of squarks versus gluino is different. In the first spectrum, labeled “˜qGGM,” the
physical squark masses are just under 1 TeV, while the physical gluino is about 1.4 TeV.
SQCD production is dominated by squarks, and decays into winos and binos are roughly
democratic. In the second spectrum, “˜gGGM,” the situation is approximately reversed,
with an 800 GeV gluino and 1.5 TeV squarks. Production in this spectrum is dominated
by gluinos, which decay through off-shell squarks. These decays are highly biased towards
winos, due to the larger $SU(2)_L$ couplings.\textsuperscript{18} A full list of input parameters for both spectra
is given in table I.\textsuperscript{19}

We used \textsc{softsusy v3.0.7} \textsuperscript{46} to extract the physical mass spectrum from our
messenger-scale parameters. These are presented in table II.\textsuperscript{19}

\textsuperscript{18} SQCD does not discriminate between squark chiralities, but the diagrams with off-shell squarks are
weighted by the couplings into the final electroweak gauginos. This is to be contrasted with gluino decays
into on-shell squarks, where both chiralities are produced equally, and the couplings to winos and binos
simply determine the squark decay rates. This latter observation also applies to the ˜qGGM spectrum for
events with gluinos.

\textsuperscript{19} Note, that while the spectrum ˜gGGM is perfectly viable, the spectrum ˜qGGM has 112 GeV Higgs, which
is excluded in the Higgs-sector decoupling limit. We use this spectrum for illustration purposes only.
Uplifting the Higgs to the experimentally allowed range is not difficult \textsuperscript{33}, and practically will not
change our conclusions (but note that other particles in the Higgs sector might be modified).
|                  | $\tilde{q}$GGM | $\tilde{g}$GGM |
|------------------|----------------|--------------|
| $\tilde{g}$       | 1403           | 823          |
| $\tilde{u}_L/\tilde{d}_L$ | 934   | 1555         |
| $\tilde{u}_R$     | 956            | 1568         |
| $\tilde{d}_R$     | 934            | 1555         |
| $\tilde{t}_1$     | 877            | 1454         |
| $\tilde{t}_2$     | 954            | 1512         |
| $\tilde{b}_1$     | 908            | 1500         |
| $\tilde{b}_2$     | 934            | 1553         |
| $\tilde{\chi}^0_1$ | 301    | 313          |
| $\tilde{\chi}^0_2$ | 338    | 362          |
| $\tilde{\chi}^0_3$ | 451    | 754          |
| $\tilde{\chi}^0_4$ | 484    | 764          |
| $\tilde{\chi}^{+}_1$ | 333   | 362          |
| $\tilde{\chi}^{+}_2$ | 483   | 769          |
| $\tilde{c}_R$     | 361            | 362          |
| $\tilde{\tilde{t}}_L$ | 235   | 232          |
| $\tilde{\nu}$     | 221            | 218          |
| $\tilde{\tau}_1$  | 233            | 227          |
| $\tilde{\tau}_2$  | 361            | 364          |
| $h$               | 112            | 115          |
| $H^0/H^+/A^0$     | 520            | 800          |

**TABLE II:** Physical masses (in units of GeV) in the example spectra.

### B. Generation and Reconstruction of Events

We utilized several programs in order to generate and reconstruct our signal events. These include

- **MadGraph/MadEvent v4.3.0** [47] for generation of generic $2 \rightarrow 2$ SUSY pair production in 14 TeV $pp$ collisions. (100k events for each spectrum)
• **BRIDGE v2.15** [41] for calculating branching ratios of SUSY particles and simulating decay chains.

• **PYTHIA v6.4.14** [48] interface for MadGraph to shower and hadronize the events.

• **FastJet v2.3.4** [49] for jet reconstruction of the particle-level events.

After hadronization, event reconstruction proceeds as follows. We separate out leptons (electrons and muons) with $p_T$ above 5 GeV and $|\eta| < 2.5$, and check them for isolation. We scalar-sum the $p_T$ of the lepton with the $p_T$s of all other non-leptonic (and non-invisible) particles within an $\eta-\phi$ cone of size 0.4. If the lepton constitutes 90% or more of the total $p_T$, then we consider it “tight.” Failing this, if the $p_T$ of the other particles tallies to less than 10 GeV, we consider it “loose.” (This second class of leptons will be be used to keep more signal in trileptonic events.) We set aside leptons which fail both of these criteria for clustering into jets.

In the spectra discussed above, nearly 90% of leptons produced in gaugino decay will be identified as tight, and most of the rest as loose. The leptons produced in the three-body slepton decays will be softer, and therefore more difficult to identify and isolate. In particular, we lose up to 30% of them due to our 5 GeV $p_T$ threshold. (See Fig. 7 for the complete $p_T$ distributions. Note the large tails due to the boost of the sleptons.) The efficiency for detecting the leptons that pass the threshold depends on the amount of jet activity in the event, varying from almost unity for squark pair production down to about 50% for gluino pair production. $\mathcal{O}(50\%)$ of these leptons are identified in the loose category.

After identifying the set of isolated leptons, we proceed to cluster all of the remaining non-invisible particles in the event into jets using the Cambridge/Aachen algorithm with $R = 0.4$. We keep jets with $p_T > 20$ GeV and $|\eta| < 2.5$.

Since we will focus on heavy SQCD production events, we apply cuts on jet activity and missing energy. We demand at least two jets above 300 GeV of $p_T$, and $E_T$ of at least 200 GeV.\(^{20}\) We do not consider events with zero leptons, though these would of course be interesting to investigate in a more complete analysis. We consider events with one lepton

\(^{20}\) These cuts have not been optimized. A more complete analysis may achieve better signal vs background discrimination. For example, we might demand larger jet multiplicities but with a looser $p_T$ cut. Such a cut could be more inclusive of gluinos decaying through off-shell squarks.
FIG. 7: The parton-level $p_T$ spectrum of leptons produced in three-body slepton decay, for the $\tilde{q}$GGM spectrum (left panel) and $\tilde{g}$GGM spectrum (right panel). In the slepton rest frame, the lepton energy ranges from 0 to 14 GeV, with an average of about 7 GeV.

if it is tight, and if the transverse mass of the lepton and missing energy vector is above 100 GeV, to veto $W$ backgrounds. An event with more than one lepton must have at least two tight leptons, or else we discard it. In particular, trilepton events may have a single loose lepton. This keeps $O(50\%)$ more of the signal in that channel, while the backgrounds remain small. We also neglect events with any OSSF dilepton pairs between 80 GeV and 100 GeV, in order to avoid incorporating $Z$s (either from backgrounds or produced in SUSY cascades) into our analysis.

We present leading-order cross sections for the $\tilde{q}$GGM and $\tilde{g}$GGM spectra, before and after reconstruction and cuts, in appendix [B]

C. Backgrounds

We simulate the leading backgrounds from SM processes that generate hard leptons and neutrinos through electroweak boson decays. These include

- $t\bar{t}$+jets. Matched using $k_T$-MLM at 20 GeV, up to two additional jets. (6M events, 1.9M after matching veto)

- $WWjj$ (opposite- and same-sign). In MadGraph, we use cuts $\Delta R_{jj} > 0.4$, $p_{Tj} > 150$ GeV. (70k events)

- $l\nu jj$ via on-shell $W$ (including $\tau$s). $\Delta R_{jj} > 0.4$, $p_{Tj} > 150$ GeV, $E_T > 150$ GeV. (500k events)
• $\tau^+\tau^- jj$. $\Delta R_{jj} > 0.4$, $p_{Tj} > 150$ GeV. (500k events)

We decay the $t\bar{t}$ and $WWjj$ samples with BRIDGE both in semileptonic and in dileptonic channels, including taus. The all-hadronic mode was found to give negligible contribution given our cuts above.

There will also be contributions from $(l^+l^-)+\text{jets}$ (in addition to the tau mode above), $(l^+l^-)W+\text{jets}$, and $(l^+l^-)(l^+l^-)+\text{jets}$. None of these backgrounds are expected to be significant, and they are indeed found to be subdominant in other SUSY analyses (see, e.g., [50]). We have explicitly checked $(l^+l^-)W+\text{jets}$, which should be the dominant electroweak background in the trilepton channel, in particular $(\tau^+\tau^-)W+\text{jets}$ in light of our transverse mass cut. We have verified that it is small, with a total cross section in the trileptonic channel, after cuts, of 0.04 fb. We do not explicitly include it in the analysis.

The monoleptonic channel may be polluted by generic QCD events with heavy flavor decays. However, our cuts on tightness of the lepton and on $E_T$ will significantly reduce these. We do not investigate this background here, but note that generic QCD has been shown to be negligible in other monolepton SUSY analyses (see again [50]). These usually use a higher $p_T$ cut on the lepton, but we do not find that this has a significant effect on our results below.

There is an additional subtlety with the monoleptonic channel. Without additional activity from heavy flavor, events with a single leptonic $W$ decay will almost never pass our 100 GeV cut on transverse mass (section V B). In a more realistic simulation, most of the passing events would probably come from the resolution tail of the detector. However, we do not incorporate any resolution smearing in our nominal analysis. To get some sense of how large of an effect this might be, we smeared the transverse mass by 20% and checked how many events pass the cut. The signal is only marginally affected, but the surviving semileptonic $t\bar{t}+\text{jets}$, $Wjj$, and semileptonic $WWjj$ backgrounds increase by factors of roughly 3, 5, and 10, respectively. These are still quite small with respect to the signals. (They can also be significantly attenuated with modest additional cost to the signal by simply using a higher transverse mass cut.)

Leading-order cross sections for the backgrounds, before and after reconstruction and cuts, can be found in appendix [B]
D. Analysis of Events

Here we present the results of the analyses of section IV as applied to our two sample spectra, $\tilde{q}$GGM and $\tilde{g}$GGM, incorporating backgrounds. Events are weighted to correspond to 100 fb$^{-1}$ of integrated luminosity. While pure counting in multiple channels will already indicate the presence of SUSY (and even suggest the presence of a sneutrino NLSP) long before this amount of luminosity is acquired, we choose to present this longer-term goal so that statistics are good enough to clearly see the shapes in all of our proposed kinematic distributions.

Indeed, if lepton fakes and missing energy are well-understood early on, a clear excess of events in the monoleptonic channel may already be visible with as little as a few 100 pb$^{-1}$ of data, even at the planned initial operating energy of 10 TeV. Subsequent progress will depend somewhat on how soon 14 TeV becomes available, with $3 \sim 4$ times higher signal cross sections.$^{21}$ In any case, relatively background-free samples of same-sign dilepton and trilepton events would start to become available with a few fb$^{-1}$. Opposite-sign dileptons should also emerge with statistical significance over backgrounds around this point. The presence of a near-flavor-universal excess of OS over SS could probably be inferred by a few 10’s of fb$^{-1}$, with shape information becoming progressively better above that. Of course, spectra with lighter colored superpartners would have higher rates, and might require less running to achieve the same level of statistics.

Fig. 8 shows the lepton counting at 100 fb$^{-1}$, 14 TeV, after application of our analysis cuts. Fig. 9 shows a more refined view of the individual channels in the dileptonic events. We see that the ratio of monoleptonic:dileptonic is of order 3:1, which is close to what we expect from the naive counting presented in section IV.

Backgrounds, dominated by $t\bar{t}+\text{jets}$$^{22}$, are clearly not obscuring the $\tilde{q}$GGM signal. They are more important for $\tilde{g}$GGM, though the dilepton mass shape is quite different. The background can of course be further reduced with more aggressive or more tailored cuts, but we do not investigate this explicitly.

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$^{21}$ This factor applies both before and after our cuts on the signal. We have not explicitly investigated the backgrounds at 10 TeV, but do not expect them to become significantly more important relative to the signal.

$^{22}$ We parenthetically note that in most of the events passing cuts, one or both of the two leading jets typically do not come from the top’s decay.
In Fig. 10 we show the dilepton invariant mass spectrum in the OS and SS channels. Fig. 11 displays the OS minus SS subtraction, which picks out the OS excess. In both plots, the $Z$ mass window $80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$ is blinded. Note that we could avoid this if we separately considered opposite-flavor channels, which are free of $Z$ contamination.

In the spectrum $\tilde{q}$GGM we expect to see two bumps of comparable size, corresponding to wino and bino, sitting one on top of the other. Using equation (13), we predict peaks at 31 and 40 GeV. This is quite consistent with what we see on the sign-subtracted invariant mass plot. In $\tilde{g}$GGM spectrum, most of the decays proceed through wino, rather than bino. Hence we expect to see only one bump around 50 GeV, and this is indeed what is observed.

We turn now to the dileptonic invariant mass in the trileptonic channel, forming lepton pairs according to the procedure discussed in subsection IV C. We show this distribution in Fig. 12. This channel essentially lacks any backgrounds after the cuts we impose, and reproduces the same features as the dileptonic sign-subtracted invariant mass.

Finally we analyze the leading-jet/leading-lepton invariant mass in Fig. 13. Since in the $\tilde{g}$GGM spectrum, gluinos decay through the squarks off-shell, we do not see any clear feature. However, in the $\tilde{q}$GGM spectrum we see an edge in the distribution, corresponding to the cascade decay $\tilde{q} \rightarrow \tilde{\chi} \rightarrow \tilde{t}/\tilde{\nu}$. The theoretically predicted endpoint is around 625 GeV, and is easily visible.
FIG. 9: Dilepton channels for the $\tilde{q}$GGM spectrum (left panel) and $\tilde{g}$GGM spectrum (right panel). (The histograms are stacked.) Note that OSSF is slightly reduced due to the $Z$ veto.

FIG. 10: Dilepton invariant mass distribution for OS and SS categories, for the $\tilde{q}$GGM spectrum (left panel) and $\tilde{g}$GGM spectrum (right panel). The $Z$ mass window has been blinded. (Backgrounds are almost purely OS.)

VI. CONCLUSIONS AND OUTLOOK

In this paper we began investigating the collider signals of the largely unexplored region of MSSM parameter space with NLSP sneutrinos. We showed that a large portion of this region has distinctive collider signatures at the LHC. In particular, we focused on strong production modes for spectra with $\mathcal{O}$(TeV) colored superpartners, approximate flavor degeneracy in the LH sleptons, and RH sleptons mostly bypassed in the decay chains.

We found that these spectra lead to interesting multilepton signals. A large fraction of
FIG. 11: Dilepton invariant mass distribution, applying the OS minus SS subtraction (including backgrounds), for the $\tilde{q}$GGM spectrum (left panel) and $\tilde{g}$GGM spectrum (right panel). The $Z$ mass window has been blinded. Error bars are representative of 100 fb$^{-1}$ statistics.

FIG. 12: Trilepton invariant mass distribution, obtained using the technique described in subsection IV C, for the $\tilde{q}$GGM spectrum (left panel) and $\tilde{g}$GGM spectrum (right panel).

SUSY events are monoleptonic or dileptonic. The dileptons are mostly characterized by a broad distribution with no sign or flavor correlations, but they are accompanied by a sizable excess of sign-correlated dileptons. Unlike many SUSY dilepton signals, this excess is completely flavor-universal. It has a unique shape which contains information about the mass splittings within the spectrum. In addition, the trilepton channel has an appreciable rate. If analyzed carefully, it can provide strong confirmation of the physics inferred from the dileptons. All together, these leptonic signatures are quite difficult to fake within alternative spectra in the MSSM, and their observation should be taken as highly suggestive evidence.
for a sneutrino NLSP.

We also proposed specific ways to analyze these signals. In particular, we used simulations of two representative spectra to demonstrate that one can extract the signal in the dileptonic channel using sign subtraction. The signature in the trileptonic channel can also be purified, and combinatorial background significantly reduced, by choosing events with a unique opposite-sign pairing between the softest lepton and one of the two hardest leptons. This technique works because the softest lepton is usually the one emitted from the $W^*$ in the decay of the slepton down to the sneutrino.

Of course, we could not cover all possible MSSM spectra with $\tilde{\nu}$-NLSP. In particular, we did not analyze spectra where the RH slepton plays an active role in the decay chains. Though these certainly share some common features with the spectra analyzed here, their collider signatures will be much more “leptogenic,” producing up to three or four leptons from a single decay chain. Indeed, spectra with active RH sleptons can be treated as close relatives of the spectra studied in [51, 52], with the roles of the LH and RH sleptons interchanged. We will study spectra with RH sleptons in detail in a forthcoming paper [9].

In this paper, we tried to address only a very broad question, namely whether we can identify spectra with $\tilde{\nu}$-NLSP utilizing some well-defined collider signals. Taking our results as evidence that this is possible (at least in a large portion of the allowed parameter space), we face further interesting questions. For example, if these signals are actually discovered, then are there any additional clues that tell us whether we are observing a high-scale or
low-scale mediation scenario? One way to answer this question might be to study flavor non-degeneracy in the sleptons and sneutrinos. We have avoided explicit analysis of $\tau$s, but dedicated study of their production in SUSY events could provide useful information. It would be very interesting to see how feasible such a study might be at the LHC.

It would also be interesting to extend these studies to more remote parts of the parameter space. For example, we might consider spectra where a neutralino resides between the slepton and sneutrino. It is also very important to understand the current experimental bounds on all these scenarios from LEP and the Tevatron. To the best of our knowledge, these studies have not been performed yet.

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Appendix A: Analytic approximations to opposite-sign dilepton mass distributions

The dilepton invariant mass spectrum from the chain $\tilde{\chi}^0 \rightarrow l_i^- \tilde{l}_i^+ \rightarrow l_i^- (l_j^+ \nu_j \tilde{\nu}_i^-)$ asymptotes to a polynomial in the limit where the sneutrino goes nonrelativistic in the slepton’s rest frame (or equivalently, when $m_{l_i} - m_{\nu_i} \ll m_{l_i}$). Assuming constant matrix element, the normalized distribution takes the form

$$\frac{dP}{dm_{l_l}} = \frac{6}{m_{\max}^6} m_{l_l} \left( m_{\max}^2 - m_{l_l}^2 \right)^2,$$

where $m_{\max}$ is as in equation (13). This distribution peaks at $m_{\max}/\sqrt{5}$. Putting in the electroweak current-current matrix element for the slepton decay, this becomes

$$\frac{dP}{dm_{l_l}} = \frac{5}{m_{\max}^{10}} m_{l_l} \left( m_{\max}^2 - m_{l_l}^2 \right)^3 \left( m_{\max}^2 + 3m_{l_l}^2 \right),$$
which peaks at
\[ \sqrt{1 + \sqrt{28}} \frac{m_{\text{max}}}{27} \approx (0.48) m_{\text{max}}. \]

Appendix B: Cross sections

In this appendix, we summarize leading-order production cross sections for our signals and backgrounds in section V.

The following table shows the cross sections (in fb) for the different super-QCD pair production modes for our two sample spectra.

| spectrum | $\tilde{g}\tilde{g}$ | $\tilde{g}\tilde{q}$ | $\tilde{q}\tilde{q}^*$ | $\tilde{q}\tilde{q}$ |
|----------|-----------------|-----------------|-----------------|-----------------|
| $\tilde{g}$GGM | 650 | 310 | 8 | 36 |
| $\tilde{q}$GGM | 10 | 240 | 250 | 440 |

The next table lists the inclusive super-QCD pair production cross sections (in fb) for our sample spectra, broken down into multilepton channels, before and after reconstruction and cuts.

| | $\tilde{q}$GGM | $\tilde{g}$GGM |
|----------------|----------------|----------------|
| partonic reco | partonic reco | partonic reco |
| total | 950 | 310 | 1000 | 148 |
| 0l | 450 | 200 | 350 | 85 |
| 1l | 350 | 80 | 450 | 48 |
| 2l | 120 | 26 | 190 | 15 |
| 3l | 19 | 3.6 | 27 | 1.4 |
| 4l | 1.9 | 0.3 | 1.7 | 0.04 |

The last table lists our major backgrounds, including cross-sections at generator-level and in the various multi-lepton channels after reconstruction. The matched $t\bar{t}$ +jets sample is inclusive, while rest of the backgrounds were produced with generator-level cuts, as described in subsection V.C. When we observed no events after cuts, we placed a “0” in the entry, but this is roughly to be understood as a limit of $\lesssim 1$ event after a 100 fb$^{-1}$ run (i.e., cross section less than about 0.01 fb).
|                | dilep $t\bar{t}$ +jets | semilep $t\bar{t}$ +jets | dilep $WWjj$ | semilep $WWjj$ | $Wjj \rightarrow (l/\tau)\nu jj$ | $\tau^+\tau^-jj$ |
|----------------|------------------------|------------------------|-------------|--------------|----------------------|------------------|
| generated      | $6.3 \times 10^4$      | $2.5 \times 10^5$      | 104         | 418          | 4000                 | 4400             |
| 1l reco        | 2.1                    | 0.40                   | 0.60        | $\sim 0.02$  | 0.31                 | 0                |
| 2l (OS) reco   | 1.7                    | 0                      | 0.88        | 0            | 0                    | 0.75             |
| 2l (SS) reco   | 0                      | 0                      | 0.09        | 0            | 0                    | 0                |
| 3l reco        | $\sim 0.03$            | 0                      | 0           | 0            | 0                    | $\sim 0.008$     |

[1] T. Falk, K. A. Olive, and M. Srednicki, *Heavy Sneutrinos as Dark Matter*, Phys. Lett. **B339**, 248 (1994), hep-ph/9409270.

[2] C. Arina and N. Fornengo, *Sneutrino cold dark matter, a new analysis: Relic abundance and detection rates*, JHEP **11**, 029 (2007), 0709.4477.

[3] N. Arkani-Hamed, A. Delgado, and G. F. Giudice, *The well-tempered neutralino*, Nucl. Phys. **B741**, 108 (2006), hep-ph/0601041.

[4] M. Dine and W. Fischler, *A Phenomenological Model of Particle Physics Based on Supersymmetry*, Phys. Lett. **B110**, 227 (1982).

[5] M. Dine and W. Fischler, *A Supersymmetric GUT*, Nucl. Phys. **B204**, 346 (1982).

[6] L. Alvarez-Gaume, M. Claudson, and M. B. Wise, *Low-Energy Supersymmetry*, Nucl. Phys. **B207**, 96 (1982).

[7] M. Dine, A. E. Nelson, and Y. Shirman, *Low-energy dynamical supersymmetry breaking simplified*, Phys. Rev. **D51**, 1362 (1995), hep-ph/9408384.

[8] M. Dine, A. E. Nelson, Y. Nir, and Y. Shirman, *New tools for low-energy dynamical supersymmetry breaking*, Phys. Rev. **D53**, 2658 (1996), hep-ph/9507378.

[9] A. Katz and B. Tweedie, *to appear* (2009).

[10] P. Meade, N. Seiberg, and D. Shih, *General Gauge Mediation*, Prog. Theor. Phys. Suppl. **177**, 143 (2009), 0801.3278.

[11] C. Csaki, A. Falkowski, Y. Nomura, and T. Volansky, *New Approach to the $\mu$-$B\mu$ Problem of Gauge-Mediated Supersymmetry Breaking*, Phys. Rev. Lett. **102**, 111801 (2009), 0809.4492.

[12] Z. Komargodski and N. Seiberg, *$\mu$ and General Gauge Mediation*, JHEP **03**, 072 (2009), 0812.3900.
[13] P. Meade, M. Reece, and D. Shih, *Prompt Decays of General Neutralino NLSPs at the Tevatron* (2009), 0911.4130.

[14] G. D. Kribs, A. Martin, and T. S. Roy, *Supersymmetry with a Chargino NLSP and Gravitino LSP*, JHEP 01, 023 (2009), 0807.4936.

[15] L. M. Carpenter, *Surveying the Phenomenology of General Gauge Mediation* (2008), 0812.2051.

[16] A. Rajaraman, Y. Shirman, J. Smidt, and F. Yu, *Parameter Space of General Gauge Mediation*, Phys. Lett. B678, 367 (2009), 0903.0668.

[17] L. M. Carpenter, M. Dine, G. Festuccia, and J. D. Mason, *Implementing General Gauge Mediation*, Phys. Rev. D79, 035002 (2009), 0805.2944.

[18] M. Buican, P. Meade, N. Seiberg, and D. Shih, *Exploring General Gauge Mediation*, JHEP 03, 016 (2009), 0812.3668.

[19] D. E. Kaplan, G. D. Kribs, and M. Schmaltz, *Supersymmetry breaking through transparent extra dimensions*, Phys. Rev. D62, 035010 (2000), hep-ph/9911293.

[20] Z. Chacko, M. A. Luty, A. E. Nelson, and E. Ponton, *Gaugino mediated supersymmetry breaking*, JHEP 01, 003 (2000), hep-ph/9911323.

[21] J. L. Feng, A. Rajaraman, and B. T. Smith, *Minimal supergravity with\( m_{2}^{2} < 0\)*, Phys. Rev. D75, 055017 (2007), hep-ph/0611185.

[22] L. Covi and S. Kraml, *Collider signatures of gravitino dark matter with a sneutrino NLSP*, JHEP 08, 015 (2007), hep-ph/0703130.

[23] J. L. Evans, D. E. Morrissey, and J. D. Wells, *Sneutrino NLSP Scenarios in the NUHM with Gravitino Dark Matter*, JHEP 08, 005 (2008), 0807.3736.

[24] A. D. Medina, N. R. Shah, and C. E. M. Wagner, *A Heavy Higgs and a Light Sneutrino NLSP in the MSSM with Enhanced SU(2) D-terms*, Phys. Rev. D80, 015001 (2009), 0904.1625.

[25] Y. Santoso, *Signatures of Sneutrino NLSP in Gravitino Dark Matter Scenario at the LHC* (2009), 0909.4742.

[26] J. L. Feng, A. Rajaraman, and B. T. Smith, *Minimal supergravity with\( m_{2}^{2} < 0\)*, Phys. Rev. 39
[29] K. Kadota and J. Shao, Enhanced Tau Lepton Signatures at LHC in Constrained Supersymmetric Seesaw, Phys. Rev. D80, 115004 (2009), 0910.5517.

[30] M. Bolz, A. Brandenburg, and W. Buchmuller, Thermal Production of Gravitinos, Nucl. Phys. B606, 518 (2001), hep-ph/0012052.

[31] J. L. Feng, A. Rajaraman, and F. Takayama, Superweakly-interacting massive particles, Phys. Rev. Lett. 91, 011302 (2003), hep-ph/0302215.

[32] T. Kanzaki, M. Kawasaki, K. Kohri, and T. Moroi, Cosmological Constraints on Gravitino LSP Scenario with Sneutrino NLSP, Phys. Rev. D75, 025011 (2007), hep-ph/0609246.

[33] M. Dine, N. Seiberg, and S. Thomas, Higgs Physics as a Window Beyond the MSSM (BMSSM), Phys. Rev. D76, 095004 (2007), 0707.0005.

[34] Y. Nomura, D. Poland, and B. Tweedie, $\mu B$-driven electroweak symmetry breaking, Phys. Lett. B633, 573 (2006), hep-ph/0509244.

[35] Y. Nomura, D. Poland, and B. Tweedie, Minimally fine-tuned supersymmetric standard models with intermediate-scale supersymmetry breaking, Nucl. Phys. B745, 29 (2006), hep-ph/0509243.

[36] A. Brignole, J. A. Casas, J. R. Espinosa, and I. Navarro, Low-scale supersymmetry breaking: Effective description, electroweak breaking and phenomenology, Nucl. Phys. B666, 105 (2003), hep-ph/0301121.

[37] J. A. Casas, J. R. Espinosa, and I. Hidalgo, The MSSM fine tuning problem: A Way out, JHEP 01, 008 (2004), hep-ph/0310137.

[38] A. Kumar, D. Tucker-Smith, and N. Weiner, Neutrino Mass, Sneutrino Dark Matter and Signals of Lepton Flavor Violation in the MRSSM (2009), 0910.2475.

[39] G. D. Kribs, E. Poppitz, and N. Weiner, Flavor in supersymmetry with an extended R-symmetry, Phys. Rev. D78, 055010 (2008), 0712.2039.

[40] Z. Thomas, D. Tucker-Smith, and N. Weiner, Mixed Sneutrinos, Dark Matter and the LHC, Phys. Rev. D77, 115015 (2008), 0712.4146.

[41] P. Meade and M. Reece, BRIDGE: Branching ratio inquiry / decay generated events (2007), hep-ph/0703031.

[42] D. J. Miller, P. Osland, and A. R. Raklev, Invariant mass distributions in cascade decays, JHEP 03, 034 (2006), hep-ph/0510356.
[43] J. L. Feng, C. G. Lester, Y. Nir, and Y. Shadmi, *The Standard Model and Supersymmetric Flavor Puzzles at the Large Hadron Collider*, Phys. Rev. D77, 076002 (2008), 0712.0674.

[44] Y. Nomura, M. Papucci, and D. Stolarski, *Flavorful Supersymmetry*, Phys. Rev. D77, 075006 (2008), 0712.2074.

[45] Y. Nir, *Probing new physics with flavor physics (and probing flavor physics with new physics)* (2007), 0708.1872.

[46] B. C. Allanach, *SOFTSUSY: A C++ program for calculating supersymmetric spectra*, Comput. Phys. Commun. 143, 305 (2002), hep-ph/0104145.

[47] J. Alwall et al., *MadGraph/MadEvent v4: The New Web Generation*, JHEP 09, 028 (2007), 0706.2334.

[48] T. Sjostrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP 05, 026 (2006), hep-ph/0603175.

[49] M. Cacciari and G. P. Salam, *Dispelling the N^3 myth for the k_t jet-finder*, Phys. Lett. B641, 57 (2006), hep-ph/0512210.

[50] G. Aad et al. (The ATLAS), *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics* (2009), 0901.0512.

[51] A. De Simone, J. Fan, M. Schmaltz, and W. Skiba, *Low-scale gaugino mediation, lots of leptons at the LHC*, Phys. Rev. D78, 095010 (2008), 0808.2052.

[52] A. De Simone, J. Fan, V. Sanz, and W. Skiba, *Leptogenic Supersymmetry*, Phys. Rev. D80, 035010 (2009), 0903.5305.