Leptophilic Signals of a Sneutrino (N)LSP and Flavor Biases from Flavor-Blind SUSY

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Abstract

Although the sneutrino is a viable NLSP candidate with gravitino LSP, spectra of this type occupy a part of SUSY parameter space in which collider signatures are poorly studied. In this paper we will extend previous work on this topic to include sneutrino NLSP spectra with non-minimal phenomenology. Generally, these spectra exhibit very leptophilic behavior, which can be easily observed at the LHC. We show that a variety of such spectra can be analyzed with similar techniques, leading in each case to very suggestive evidence for complicated decay chains that end in sneutrinos. Amongst the variations considered, we find a simple class of spectra that produce signals with strong electron-muon asymmetries. These signals could naively be interpreted as evidence for lepton flavor violation, but can occur even with flavor-blind SUSY.
I. INTRODUCTION

The phenomenology of the Minimal Supersymmetric Standard Model (MSSM) has been an evolving topic of investigation for many years. While traditional supersymmetry (SUSY) mediation scenarios continue to remain relevant, supersymmetric signals have failed to manifest themselves over the course of several generations of colliders and precision low-energy experiments. As the constraints on the soft parameters have progressively tightened, SUSY model-building has proliferated, realizing unexplored and sometimes surprising regions of the MSSM parameter space. Given the vast number of possibilities, it is clear that we should be prepared for anything as we enter the LHC era, and that general classification of novel signals is a useful endeavor, independent of any specific UV motivation.

With this in mind, we have initiated an inquiry into the phenomenology of a broad, relatively unstudied region of the MSSM, in which the sneutrino acts like the lightest supersymmetric particle (LSP) at the LHC \[1\] in place of more standard options such as a neutralino. Such spectra have been largely neglected in part because the sneutrino is excluded as a stable thermal relic of the big bang \[2,3\], and also because it tends to be heavier than other superparticles in minimal mediation scenarios. However, spectra with sneutrino NLSP and gravitino LSP are quite cosmologically safe within a standard thermal history \[4–6\]. We have also seen that obtaining a sneutrino NLSP is straightforward both in low-scale mediation frameworks such as General Gauge Mediation \[7–9\], as well as in high-scale mediation \[10–14\].

Since it decays invisibly, the sneutrino NLSP is indistinguishable from an LSP within a collider, leading us to informally dub it an “(N)LSP.” Indeed, it would be unclear from collider data alone whether such a particle is the NLSP versus the true LSP within a non-standard cosmology, or whether it decays via \(R\)-parity-violating interactions after exiting the detector. In \[1\], we found that this class of scenarios can lead to very distinctive signatures, even within the simplest spectra. Our discussion there was limited to cases with flavor-degeneracy, small \(A\)-terms, squarks/gluinos heavier than at least one neutralino with sizable gaugino component, and right-handed (RH) sleptons playing almost no role in the cascades.

Given these assumptions, every cascade typically has a roughly 30% probability of producing an electron or muon, independent of which electroweak gauginos participate. This
is due to the fact that the NLSP sneutrino and its \( SU(2) \) partner, the charged left-handed (LH) slepton, are generally quasi-degenerate, and will be produced approximately democratically in gaugino decay. In addition, the decays of the charged LH sleptons can also produce leptons via \( W^* \) emission. In chains where the LH slepton is produced in a neutralino decay and subsequently decays leptonically, the two leptons produced will be correlated in charge but uncorrelated in flavor. Together, these features lead to three distinguishing signals:

1. high rates for multilepton events up to trilepton and even 4-lepton,

2. a flavor-blind excess of opposite-sign (OS) dileptons over same-sign (SS) dileptons with a distinctive invariant mass distribution,

3. the same OS dilepton kinematic feature contained within the trilepton sample.

Here, we seek to explore some variations on this basic scenario. First, we will relax the assumption that the RH sleptons are effectively decoupled from phenomenology. This means that we will consider spectra where \( m(\tilde{e}_R) < m(\tilde{B}) \), and in which production of the mostly-Bino neutralino in squark/gluino cascades is not too small. We call these “RH-active” spectra. Decay chains with RH sleptons will contain additional electron and muon emissions, leading to a richer structure of multileptonic signals. Besides overall higher lepton multiplicities—with significant three-, four-, and five-lepton signals—there will be several overlapping kinematic distributions in most channels. We note that these spectra share much in spirit with the “leptogenic” SUSY scenario of [15, 16], though with the ordering of RH versus LH sleptons reversed, and without CHAMPs (CHArged Ma ssive Particles). In particular, every event will end with two sneutrinos instead of two quasi-stable RH sleptons, introducing different decay topologies and limiting all kinematic reconstructions.

Interestingly, RH-active spectra can also lead to highly flavor-biased signals within the first two generations, in spite of the fact that we continue to work exclusively with flavor-blind SUSY mediation with small \( A \)-terms. In some cases, left-right mixing effects can become important in the decays of not only the (mostly-)RH stau, but also the RH smuon. This can radically alter the decay chains with RH smuons with respect to RH selectrons, despite the fact that these sleptons will be nearly mass degenerate. For example, a RH smuon can mix into a LH smuon, and decay directly to the NLSP sneutrino by emitting a real or virtual \( W \). When such mixing-induced smuon decays dominate, they will lead to
$O(1)$ flavor non-universality in the multilepton signals. At first sight, the observation of such signals at the LHC could be interpreted as highly flavor non-universal slepton soft terms, similar to [17–20]. However, in our spectra, the non-universality originates entirely with the (supersymmetrized) Standard Model Yukawa couplings at tree level.

The last variation which we consider here is the class of spectra where the LH stau doublet becomes split off from the first two generations, so that $m(\tilde{\nu}_\tau) < m(\tilde{\tau}_L) < m(\tilde{\nu}_{e,\mu})$. This can happen due to Yukawa-dependent running effects in high-scale models. In the specific case that we study, all of the slepton doublets become light due to $D$-term corrections induced by a large down-type Higgs soft mass. The large soft mass further drives the flavor splitting. This possibility was pointed out in [10–13], and some of the details of its LHC phenomenology were further discussed in [21–23]. Spectra of this type are referred to as “NUHM” spectra, for non-universal Higgs mass boundary conditions. The fact that the NLSP (tau sneutrino) and NNLSP (mostly-LH stau) both carry tau-number suggests that the products of decay chains will be enriched with taus, and indeed this has been the favored collider signature discussed in the literature [21–23]. Here, we will see that the analysis techniques which we develop for more flavor-degenerate spectra can also be applied in this case, independent of the efficiency for identifying taus.

In summary, then, we will be extending our analysis of the simplest sneutrino NLSP spectra [1] to incorporate the following possibilities: a non-negligible role for RH sleptons in SUSY decay chains, either with or without flavor-dependent decays of the RH sleptons due to left-right mixing, and a significantly lighter stau doublet due to running effects from a large down-type Higgs soft mass. In all of these cases, every SUSY decay chain has several new opportunities to produce electrons and muons, leading to high rates for multilepton signals up to quite high multiplicity. We continue to concentrate on distributions within the dileptonic and trileptonic channels, as these have manageable combinatoric ambiguities and good statistics. We will see that these spectra can have significant excess of opposite-sign same-flavor (OSSF) leptons, which typify more standard spectra with a neutralino LSP. However, this excess will coexist with the characteristic flavor-uncorrelated OS signal of LH slepton production and decay, leading to independent excesses in OSSF and opposite-sign

1 Parenthetically, we note that such scenarios may be subject to constraints from $\mu \rightarrow e\gamma$, but this depends in detail on the structure of the right-handed neutrino sector.
opposite-flavor (OSOF), mismatched in normalization, shape, and in some cases electron versus muon composition. Trilepton will display an additional excess originating from chains which proceed sequentially through RH sleptons and charged LH sleptons. Again, sign and flavor information will serve as useful indicators. Together, the coexistence of all of these signals will be quite suggestive of spectra with a sneutrino NLSP, beyond the simplest cases discussed in [1].

The paper is organized as follows. In section II we discuss the decays of LH and RH sleptons. In section III, we show how the presence of RH sleptons or a light stau doublet modifies the multilepton signals characteristic of simpler sneutrino NLSP scenarios, possibly in flavor non-universal ways. We analyze several representative examples in simulation in section IV. Section V contains conclusions and discussion. Some technical details are relegated to the appendix.

II. DECAYS OF THE SLEPTONS

Our focus in this paper will be the multileptonic signals of sneutrino NLSP spectra beyond the simplest models. The leptons are dominantly produced in one of two ways: in the decays of gauginos to sleptons, and in the subsequent decay of the sleptons. Up to chargino and neutralino mixing effects, which we assume to be modest, the former production mechanism is quite simple. However, slepton decays can be multifaceted in these spectra, and here we will dedicate some discussion to these decays.

First we will briefly review the main decays of interest for the LH sleptons. We then move on to discuss the simplest, flavor universal decays of RH sleptons. Finally, we discuss RH slepton decay modes induced by left-right mixing. These modes will often dominate RH stau decays, but can also dominate RH smuon decays, leading to very striking flavor non-universal signals in the first two generations.

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2 As we will later see from simulation (section IV), this assumption is not strictly necessary, and the behavior of the leptonic channels is qualitatively unchanged even in spectra with highly mixed neutralinos. However, we will continue to make this assumption for the purpose of simplifying the discussion.
A. Left-Handed Sleptons

The decays of the LH sleptons, $SU(2)$ partners of the NLSP sneutrinos, were seen to be a crucial ingredient in our original study [1]. The situation is unchanged in the RH-active spectra which we consider here, but we present a brief review. We then proceed to discuss potentially relevant variations.

Recall that the splitting between the LH sleptons and the sneutrinos is given mostly by $D$-term interactions with the Higgs VEVs:

$$m_{\tilde{l}} - m_{\tilde{\nu}} \approx m_W^2 (-\cos 2\beta) \left(\frac{m_{\tilde{l}} + m_{\tilde{\nu}}}{m_{\tilde{l}} - m_{\tilde{\nu}}} \right).$$

One can clearly see that the splitting cannot exceed the mass of the $W$, and that any decay of the LH slepton is necessarily three-body. For example, for a doublet mass of 200 GeV, and $\tan \beta \gtrsim 3$, the splitting is about 16 GeV. Typically, the dominant diagram is the familiar electroweak decay via $W^*$ emission, as in Fig. 1. Branching fractions are as usual. 67% of decays produce jets, which are in this case relatively soft and low-multiplicity due to the smallness of the available energy. These decays will likely be quite difficult to isolate at the LHC. 11% of decays produce a tau, also a challenging signal, and sometimes indistinguishable from a prompt electron or muon production. The remaining 22% of decays result in a relatively clean electron or muon.

This lepton is completely uncorrelated in flavor with its parent slepton, and with any charged lepton produced along with the slepton. Therefore, decay chains with an intermediate LH slepton can feature a pair of opposite-sign leptons with no relative flavor structure. As discussed in [1], this leads to equal excesses of OSSF and OSOF lepton pairs, which can be seen in dilepton as well as trilepton events at the LHC. We argued that the observation of these unconventional signals would serve as strong evidence for a spectrum with sneutrino NLSP where RH sleptons are largely bypassed.
FIG. 2: Additional neutralino diagrams contributing to LH slepton decays. The diagram on the left interferes with the $W^*$ leptonic mode. The diagram on the right proceeds via a chirality-flip on the neutralino propagator.

More generally, the $W^*$ diagrams are accompanied by other diagrams involving virtual charginos, neutralinos, and, in the case of staus, heavy charged Higgses. Fig. 2 shows the neutralino diagrams, which consist of two different, mutually non-interfering cases depending on chirality flow (i.e., whether the $\tilde{l}_L$ decays into $\tilde{\nu}$ or $\tilde{\nu}^*$). These can both usually be neglected to first approximation, as long as the mass-squared difference between the neutralinos and the LH sleptons is significantly larger than $m^2_{\tilde{l}}$. Equivalently, the LH doublet should be split off from the neutralinos by an amount $O(1)$ times larger than its own internal $D$-term mass splitting. In this case, the largest correction to the $W^*$ decays naively comes from the chirality-flipping process on the right side of Fig. 2 since its rate is enhanced by $m^2_{\tilde{\chi}}/m^2_{\tilde{l}}$ with respect to the chirality preserving process. Both of these would introduce an additional population of OSSF dileptons, since the flavors of the slepton and final lepton are now correlated. However, the chirality-preserving diagrams interfere with the $W^*$ diagrams in the case of same-flavor decays, leading to larger effects than the chirality-flipping diagrams. The interference term can either enhance or deplete the OSSF signals, depending on whether the neutralino is mostly-Bino or mostly-Wino, respectively. We will not study cases where this effect is large enough to be easily observed, but we note that their dilepton signals can be somewhat similar to those of the NUHM spectra which we do study, if the closest neutralino is Bino-like. The case of interference with a mostly-Wino neutralino would, however, be quite distinctive, as it would feature an OSSF deficit from the destructive interference in same-flavor decays.\footnote{\footnotetext{For a mostly-Wino, the relative correction to same-flavor decays from interference goes like $-m^2_{\tilde{W}}/(m^2_{W} - m^2_{\tilde{l}})$. (For the Bino, we would make a sign flip and multiply by $g_1^2/g_2^2$.) For example, for a 200 GeV slepton and 260 GeV Wino, the correction is roughly $-20\%$.}}
In spectra with a light stau doublet, the effects of these additional diagrams become important for a different reason: for a LH slepton of the first two generations, 3-body decays into $\tilde{\nu}_\tau \nu_\tau$, as well as $\tilde{\tau} \tau$, can have much larger available phase space. Chirality-flipping and chirality-preserving processes each contribute significantly, leading to an observable OSSF excess beyond the OS excess from the usual $W^*$ decays. We will study spectra of this type in more detail below.

We note that we will explicitly be assuming that the gap between the tau-sneutrino and the first two generations of LH sleptons only contains the LH stau and the electron- and muon-sneutrinos. In other words, there are no chargino or neutralino states in between which could cause additional cascades. If this were the case, then we would likely lose any indication of the presence of the heavier sneutrinos in the decay chains, as their partner sleptons would more likely bypass them to undergo 2-body decays.\footnote{There are also several similar variations on the LH slepton decays in the flavor-degenerate case, which we do not pursue in detail because they are rather special. However, we mention the simplest of these for completeness. A trivial possibility is the presence of a neutralino sitting in the small mass gap between the LH sleptons and their sneutrino partners. This would typically lead to nearly 100% same-flavor decays into lepton and neutralino, bypassing the sneutrino. This “accidental” scenario would be quite difficult to discriminate from more traditional neutralino LSP spectra. Another possibility is a low SUSY-breaking scale, so that the LH slepton might directly decay to lepton and gravitino, again bypassing the sneutrino. For example, with a 200 GeV (300 GeV) sneutrino in the large tan $\beta$ limit, these decays would be comparable to the leptonic $W^*$ decays for $\sqrt{F} \sim 10$ TeV (30 TeV) $\square$. While these values are relatively small, it is in principle possible for the gravitino decays to have observable effects even for $O(1)$ larger scales. The dilepton signals would again feature an additional OSSF excess from these new decay channels.}

Of course, we may also consider taking any of the above variations in LH slepton decay patterns, and embedding them into a spectrum where RH sleptons are also important. Such scenarios could have independent OSSF contributions from LH and RH sleptons, but would otherwise largely appear identical to the RH slepton cases which we study below.

\section*{B. Right-Handed Sleptons: Flavor Universal Decays}

The RH sleptons must ultimately decay down to the LH slepton doublet. If we neglect Yukawas, the only available options are real or virtual neutralino emissions, coupling through the Bino component. While the production and decay of a RH slepton is guaranteed to produce an OSSF lepton pair, simply by conservation of quantum numbers, it is clear that...
spectra with sneutrino NLSP allow for $O(1)$ probability for production of additional leptons.

In the simplest case, a neutralino sits between the RH and LH sleptons. The RH sleptons can then decay via emission of this neutralino and a lepton, assuming the neutralino has non-negligible Bino fraction. The neutralino subsequently decays into LH sleptons or sneutrinos, potentially generating one or more additional leptons. Below, we will consider this as one of our standard decay scenarios, but there are other possibilities.

In the cases where all charginos and neutralinos are more massive than the RH and LH sleptons, decays of the RH slepton proceeds virtually. The rates for these decays generally depend in detail on the mass spectrum and mixing matrix for the neutralinos. For example, it is possible for a heavy Bino-like neutralino to contribute more than a lighter Wino-like neutralino, or for different levels of neutralinos to contribute comparably and interfere. We will assume here that a single mostly-gauge eigenstate dominates, in which case the relative branching fractions into the different flavors of LH sleptons and sneutrinos are equal up to phase space.

We show the diagrams for the different 3-body decay modes in Fig. 3. In terms of charge and flavor flows, these are no different from the equivalent processes proceeding through an on-shell neutralino. But besides the obvious changes in kinematics, there will also be a bias in charge. While an on-shell neutralino would decay with equal rate to $\tilde{l}_L^- \tilde{l}_L^-$ and $\tilde{l}_L^+ \tilde{l}_L^+$ (alternately $\tilde{\nu}^* \nu$ and $\tilde{\nu} \bar{\nu}$), the off-shell neutralino propagator is sensitive to chirality flow. In particular, processes with a chirality flip are enhanced by $O(m_{\tilde{\chi}}^2/m_{\tilde{e}_R}^2)$ compared to those without the flip, favoring decays into opposite-sign leptons. This would be an interesting effect to observe, but may be quite difficult in practice.\footnote{A very similar effect in minimal gauge mediation was pointed out in \cite{24}. In that case, decays of RH sleptons into the RH stau NLSP are also sensitive to the chirality flow.}

The production and decay of the RH slepton (via these neutralino-exchange modes) will always lead to an OSSF pair of leptons, and it will not be obvious which of these two came from the RH slepton’s decay.

The overall magnitudes of the 3-body decay widths are naively unimportant for phenomenology, as long as the decays are prompt. However, we need to know these in order to determine the branching fractions for the flavor non-universal decays, to be discussed shortly.\footnote{Direct decays to gravitinos are also technically possible. However, it is quite non-generic for these to be important except in cases of accidental mass degeneracies or very heavy gauginos.} Formulas for the partial decay widths can be found in the appendix.
FIG. 3: Decay modes of the RH sleptons through off-shell neutralinos. Note that the rates from diagrams on the right side are enhanced by $O(m_{\tilde{\chi}}^2/m_{\tilde{e}_R}^2)$ due to the mass insertions of the neutralino.

C. Right-Handed Sleptons: Flavor Non-Universal Decays from Left-Right Mixing

A more complete treatment of the decays of RH sleptons includes modes induced by left-right mixing. Naively, these are only important for staus, but we will show below that one can easily find spectra where they are also important for smuons. This can lead to highly flavor non-universal signals with respect to electrons and muons.

To start, we assume that any effects from flavor violation in the soft terms are completely absent. At the input scale, the slepton mass-squared matrices are proportional to the unit matrix, and $A$-terms are zero. These will develop flavor non-universal contributions from running, originating from the Yukawas, but their presence will not qualitatively change the picture. For simplicity, we assume that they are subdominant to the tree-level Yukawa effects.\footnote{This is the usual situation for the $A$-terms when $\tan \beta$ is large. We also note that there may be lepton flavor-violating contributions from gravity-scale mediation effects, or from running through the see-saw threshold. We further assume that these are small.} This situation naturally holds in low-scale mediation scenarios, such as (general) gauge mediation.

Given these assumptions, the dominant flavor effects in the soft masses are the left-right mixing terms induced by $(F$-term) Yukawa couplings to the Higgs VEVs. Each generation
FIG. 4: Possible two-body electroweak decays modes of the RH sleptons.

of sleptons has an independent $2 \times 2$ matrix of soft masses, of the form

$$M^2 = \begin{pmatrix} m_{\tilde{l}_L}^2 & -\mu v Y_l \sin \beta \\ -\mu v Y_l \sin \beta & m_{\tilde{e}_R}^2 \end{pmatrix}. \tag{2}$$

Here $v$ denotes the VEV of the Higgs, and $Y_l$ is the SM Yukawa coupling for lepton $l$, defined as $Y_l = m_l / (v \cos \beta)$. (We work in a basis where $\mu$ is real.) The mixing term is small compared to the soft masses, leading to a small left-right mixing angle, as long as the LH and RH sleptons are not very degenerate:

$$\delta_l \simeq \frac{\mu v Y_l \sin \beta}{m_{\tilde{e}_R}^2 - m_{\tilde{l}_L}^2} = \frac{\mu m_l \tan \beta}{m_{\tilde{e}_R}^2 - m_{\tilde{l}_L}^2}. \tag{3}$$

Usually, the effects of left-right mixing in the first two generations do not have a significant impact on collider signatures. However, we saw cases above where the RH sleptons were forced to decay down to the LH slepton doublet via 3-body processes mediated by off-shell gauginos. With left-right mixing, a RH slepton can interact with electroweak gauge bosons, opening up additional 2-body decays if $m_{\tilde{e}_R} - m_{\tilde{l}_L} \gtrsim 100$ GeV (Fig. 4). It is not difficult to find spectra where these 2-body, flavor-dependent decays become very important for smuons. However, it is practically impossible for them to be relevant for selectrons, since the Yukawa is too small. This mismatch in the behavior of RH smuons versus RH selectrons will ultimately manifest at detector level as an asymmetry between muons and electrons. While the presence of RH selectrons in a chain essentially guarantees the production of an OSSF $e^+e^-$ pair, the muon-number from RH smuons may “disappear” into sneutrinos. RH smuon decays will sometimes generate additional leptons, from $W$ or $Z$ decay, but these will be flavor-uncorrelated.

The rate for the decay of a RH slepton directly into a sneutrino via on-shell $W$ emission
is
\[ \Gamma(\tilde{e}_R \to W \tilde{\nu}) = \frac{\alpha_2^2 \delta^2 \lambda^{3/2}(m_{\tilde{\nu}}^2, m_{\tilde{e}_R}, m_W^2)}{8 m_{\tilde{e}_R} m_W^2} \]
\[ = \frac{Y_l^2 \mu^2 \sin^2 \beta \lambda^{3/2}(m_{\tilde{e}_R}, m_{\tilde{\nu}}, m_W^2)}{16\pi (m_{\tilde{e}_R} - m_{\tilde{l}_L})^2} \frac{\lambda^{3/2}(m_{\tilde{e}_R}, m_{\tilde{\nu}}, m_W^2)}{m_{\tilde{e}_R}^3} \] (4)

with
\[ \lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2xz . \] (5)

By angular momentum conservation, the decays are exclusively into longitudinal \( W \), which effectively couples as a Goldstone boson. The analogous decay into \( Z \tilde{l}_L \) is simply two times smaller than this, with the kinematic factor \( \lambda \) appropriately modified.

There is also a 2-body decay mode into a physical Higgs, with parametrically very similar rate, again controlled by Yukawas. The rate is
\[ \Gamma(\tilde{e}_R \to h \tilde{l}_L) = \frac{Y_l^2 \mu^2 \sin^2 \beta}{32\pi \alpha^2 \cos^2 \alpha} \frac{\lambda^{1/2}(m_{\tilde{e}_R}, m_{\tilde{l}_L}, m_h^2)}{m_{\tilde{e}_R}^3} , \] (6)
where \( \alpha \) is the physical Higgs mixing angle, which tends to be close to zero for large \( \tan \beta \).

These formulas should be compared to those for the 3-body RH slepton decays, which can be found in the appendix. The full parametric dependences of the relative rates are rather involved, even in kinematically simplified limits. However, we can perform a comparison of the mass-independent factors, with the understanding that there is still room for a large amount of numerical engineering. We find
\[ \frac{\Gamma_{2\text{-body}}}{\Gamma_{3\text{-body}}} \sim \frac{Y_l^2 \sin^2 \beta/16\pi}{\alpha_1^2/2^{5\pi}} \times \text{(mass factors)} \]
\[ \sim \left\{ \begin{array}{c} 2 \times 10^{-4} \\ 8 \\ 2400 \end{array} \right\} \left( \frac{\tan \beta}{10} \right)^2 \times \text{(mass factors)} \] (7)
for \((e, \mu, \tau)\), respectively. It is clear that RH selectrons will practically never decay via 2-body, whereas RH staus will very likely be dominated by 2-body, when those modes are kinematically available. The RH smuon occupies a highly sensitive point, such that the relative 2-body rate will depend on the detailed mass spectrum and \( \tan \beta \). Below, we will investigate spectra where this relative rate is both large and small.

Left-right mixing effects can also be important for more general sets of spectra, again tending to hide the muon-number in RH smuon decays. For example, we can have
\[ m_{\tilde{e}_R} - m_{\tilde{e}_L} \lesssim m_W, \] such that 2-body electroweak decays are shut off. However, 3-body electroweak decays will still contribute. If the mostly-Bino neutralino is relatively heavy and unmixed, then decays via left-right mixing may nonetheless be preferred for smuons. Another possibility is a mostly-Wino in between the RH and LH sleptons. If the neutralino mixing is small enough, RH smuons may again prefer to decay via left-right mixing. Decays into the mostly-Wino neutralino will then proceed anyway because of this mixing, but so will decays (with twice the rate) to charginos, and to gauge bosons if the phase space is available. We will not analyze these cases in detail, as they will lead to qualitatively the same effects as cases where decays into on-shell electroweak bosons dominate.

### III. LEPTONIC SIGNALS

We now describe our main signals in detail, before moving on to collider studies in section IV. We will first discuss the generic multileptonic signals of RH-active spectra. We will then focus on the signals with the highest rates and the least combinatoric ambiguities, namely dileptonic and trileptonic channels. Subsequently, we will see how flavor non-universalities can manifest in these channels, if electroweak decays of the RH smuons are important. Finally, we will discuss the tau-independent signals of the NUHM spectra, and how the techniques for investigating RH-active spectra can also apply in this case.

#### A. High-Multiplicity Signals of RH-Active Spectra

As we have seen in section II, chains with a RH slepton can potentially generate a large number of leptons. The most extreme case would be \( \tilde{\chi}_0 \to l\tilde{e}_R \to lll\tilde{\nu}_L \to lll(l\nu\tilde{\nu}). \) If this were to occur on both sides of an event, the number of leptons would tally to eight. Of course, this exceptional class of events is also quite rare, since many branching fraction penalties and detection efficiencies would have to be paid. But this still tells us that we can expect these events to be quite “leptophilic.”

Such behavior contrasts with that of spectra where RH sleptons do not significantly participate, where we were relatively lucky to get an observable 4-lepton signal after a 100 fb\(^{-1}\) LHC run. There, neither the production nor the decay of \( \tilde{l}_L \) was guaranteed to produce a lepton. We nonetheless could expect to find significant dilepton and trilepton...
signals. With spectra where RH sleptons are produced with an appreciable rate, we will see below that we might reasonably find observable multilepton rates up to 5-lepton or 6-lepton, with healthy populations in the lower-multiplicity bins. Needless to say, the backgrounds for such dramatic signals are small.

Similar behavior was pointed out in [16] in the context of low-scale gaugino mediation. This is not surprising, given that the spectra which we analyze here are in some cases nearly the same, but with the ordering of the LH and RH sleptons reversed. However, we point out that there will always be significant differences in the phenomenology of these spectra. The specific scenario investigated in [16] contained a metastable mostly-RH stau as the NLSP, leading to striking CHAMP signals. Even if the SUSY-breaking scale were lowered, such that RH sleptons decay promptly, then every chain is guaranteed to independently produce an OSSF lepton pair or tau pair. Such a scenario would be much more leptophilic than ours.

It is also possible that RH selectrons and smuons first decay to stau, which then decays to tau and gravitino, leading to at least four taus per event, in addition to the two OSSF pairs. If even a fraction of these taus and leptons are detected with good efficiency for every event, they will still be quite suggestive of scenarios with RH slepton NLSP.

Although high-multiplicity leptonic channels will serve as very clean evidence for new physics, we will not utilize signals with four or more leptons for any analysis beyond simple counting. The main reasons for this are the formidable combinatorial uncertainties and the overall lower statistics. In any case, the only new kinematic information contained in these events would be the 4-lepton distributions from a single decay chain. For the purposes of this study, we consider these distributions as lost, and instead we will concentrate on the dileptonic and trileptonic events.

B. Dileptons

In [1], the dileptonic distributions had two major classes of contributions. The first was from events where one chain produced opposite-sign, flavor-uncorrelated leptons from LH slepton production and decay (Fig. 5), and the other chain produced no visible leptons. The second contribution came from events where each chain produced a single lepton (from either slepton production or decay). These leptons were totally uncorrelated in both sign and flavor. The full set of SUSY dilepton invariant mass spectra contained a broad contribution
from this latter class of events, equally distributed between all sign and flavor bins. The correlated leptons from a single chain, on the other hand, led to a more localized bump, which appeared with equal rates in OSSF and OSOF channels. The correlated distribution could be extracted using a simple sign-subtraction procedure, and its peak could be used to infer relationships between the gaugino, LH slepton, and sneutrino masses:

$$m_{\text{peak}}^{ll} \approx 0.48 \sqrt{\left(m_{\tilde{\chi}}^2 - m_{\tilde{l}}^2\right)\left(m_{\tilde{l}}^2 - m_{\tilde{\nu}}^2\right)}.$$  

(8)

These signals will persist in RH-active spectra, but there will also be one qualitatively new contribution. The sub-cascade $\chi_a^0 \rightarrow \tilde{e}_R \rightarrow \chi_b^{0(\ast)}$ (see Fig. 5) produces two leptons correlated in both sign and flavor. When these are the only leptons produced in a chain, and the other chain in the event produces no leptons, a new dilepton excess is generated in the OSSF channel. This signature is well-known in traditional spectra with a neutralino LSP, where it is separated from the uncorrelated dilepton distribution by using a flavor-subtraction, OSSF-OSOF. In sneutrino NLSP spectra, this signal will coexist with the OS distribution from LH slepton production/decay, as well as the background of totally uncorrelated SUSY dileptons. The situation is illustrated in Fig. 7.

The shape of the OSSF excess depends on further details of the decay process. In the case that a neutralino sits below the RH slepton, such that the RH slepton can undergo a 2-body decay, the distribution will be of the characteristic ramp-and-edge shape. If the decays are 3-body, then the distribution takes on a more bump-like shape, similar to the shape of the OS excess. However, the distribution will usually be skewed to some extent toward higher masses.

Clearly, as Fig. 7 suggests, extracting both of the independent kinematic shapes from the different sign and flavor channels is slightly nontrivial, but still straightforward. We should
FIG. 6: The sub-cascade responsible for the OSSF dilepton excess in chains with RH sleptons. Neutralino \( \chi_0^b \) can be either on- or off-shell, and in the latter case we usually have \( a = b \).

FIG. 7: Illustration of the dilepton invariant mass distributions characteristic of RH-active spectra, broken down into sign/flavor channels. The independent contributions from LH sub-cascades, RH sub-cascades, and uncorrelated dileptons are shown in teal, red, and brown, respectively.

simply perform two independent subtractions: OSSF-OSOF to reveal the RH contribution, and OSOF-SSOF to reveal the LH contribution.\(^8\) Unfortunately, it would be impossible at this level of analysis to independently extract the LH contribution within the OSSF channel, and verify that it is equal to the contribution within the OSOF channel. However, the crucial observation at this point, already suggestive of the presence of sneutrinos in the chains, is that the OSOF-SSOF subtraction gives a nonzero result at all. More realistically, we will require that this subtraction gives a statistically significant excess above opposite-sign, flavor-uncorrelated backgrounds from the Standard Model, such as \( t\overline{t} \). We will demonstrate that this is possible in section IV.

\(^8\) It is possible (though not generic) to get sign correlations in the contributions from leptons produced in independent decay chains, due to biases in production. In that case, the shapes in the OS and SS channels will likely be very similar, but their normalizations could be different. It would then still be possible to perform a weighted OSOF-SSOF subtraction, such that the high-mass tail is canceled off.
More generally, it is possible that the OSSF contribution from LH sleptons has a different normalization from those in the OSOF channel, for example due to the interference effects mentioned in subsection II A. While we have just emphasized that this cannot be independently checked, we note that with high enough statistics it may be possible to see additional peaks or dips in the shape of the OSSF-OSOF excess. The presence or absence of such features becomes particularly informative if the OSSF-OSOF and OSOF-SSOF shapes are sufficiently distinct.

C. Trileptons

The trileptonic channel will also have a sizable signal, more so than in the case without the RH sleptons. Originally, the main way to obtain trilepton was to have one chain produce two leptons from LH slepton production and decay (Fig. 5), and the other chain to produce one additional lepton. The combinatorial ambiguities were therefore fairly simple, and we demonstrated in [1] a straightforward way to identify which two leptons were produced in the same chain. Now, this channel can have a variety of contributions from the production and decay stages of both RH and LH sleptons, including the option for all three leptons being produced in the same chain.

Let us start analyzing the possibilities by categorizing the sign and flavor content of the trileptons. Generally, the majority of these events will have two same-signed leptons and a single “uniquely-signed” lepton. In other words, trileptonic events with all leptons of the same sign will be subdominant. For example, if the leptons were all totally uncorrelated, only 1/4 of the events would be fully same-signed. More realistically, this fraction will be even smaller, since there are often physical sign correlations, most obviously in the OS dileptons produced in either RH or LH production/decay. We will subsequently focus our analysis exclusively on the cases with a uniquely-signed lepton, since we do not expect all-same-signed to carry much useful kinematic information. However, the observation of same-signed trilepton events is yet another clue to the simultaneous presence of RH and LH sleptons, and may serve as an extremely clean (re-)discovery signal.

Given that we have one uniquely-signed lepton, we can further classify the flavor structure of these events. We compare the flavor of the uniquely-signed lepton with the flavors of the two same-signed leptons, leading to three distinct cases:
• SFSF - both parings are of the same flavor, those are either all-electron or all-muon events,

• SFOF - one pair is of the same flavor and the second pair is of the opposite flavor,

• OFOF - both pairings include opposite flavors.

We can now perform counting experiments within these three channels, to attempt to deduce the composition of the events.

First, consider spectra with relatively inactive RH sleptons, where all trilepton events contain a LH slepton production/decay. In this case, while two of the leptons are sign-anticorrelated, the flavors of all three leptons are completely uncorrelated. For example, if the uniquely-signed lepton is an $e^-$, then there is equal probability for the same-signed pair to be $e^+e^+, e^+\mu^+, \mu^+e^+$, and $\mu^+\mu^+$. This correspond to SFSF, SFOF, SFOF, and OFOF, respectively. Quite generally, then, we expect the counting ratio OFOF:SFOF:SFSF to be 1:2:1.

Now suppose instead that the trilepton contribution is exclusively from RH slepton production/decay in one chain, with additional uncorrelated lepton, either emitted in the other chain or in a subsequent LH slepton production or decay. The first process is guaranteed to produce an OSSF pair, and one of these is in turn guaranteed to be the uniquely-signed lepton in the event. Given that one of the remaining leptons is perfectly flavor-correlated with this, and the other perfectly flavor-uncorrelated, we expect equal contributions to SFOF and SFSF, and vanishing OFOF. We therefore get OFOF:SFOF:SFSF of 0:1:1.

RH-active sneutrino NLSP spectra will exhibit a superposition of 1:2:1 and 0:1:1, with the latter represented in proportion to the amount of RH slepton production. The observation of both of these contributions added together would serve as a powerful supplement to the interpretation already suggested by the dilepton analysis. The simplest way to check this is to first verify the presence of a substantial OFOF contribution, and then to add together OFOF and SFSF, and see if the sum matches SFOF.

There will also be additional flavor-uncorrelated contributions, even from chains with RH sleptons. For example, we may fail to reconstruct one of the leptons from its production or

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Note that $e^+\mu^+$ and $\mu^+e^+$ are indeed distinct. The general event structure is $l^-_i l^+_j l^+_k$, with each of the three leptons $(i,j,k)$ produced in independent, flavor-blind subprocesses.
decay, and pick up two other unrelated leptons. However, these events do not tend to be very common. In spectra with LH and RH together, on the other hand, the flavor-uncorrelated events would usually constitute a major fraction of the trileptons. A simple indicator of the presence of the sneutrino NLSP is therefore the relative size of the OFOF, which is nominally absent or small for trilepton signals dominated by RH. Equivalently, we should pay attention to the fraction of trilepton events that lack an OSSF pairing.

Having established the basic trilepton sign/flavor channels, we can now proceed to investigate kinematic distributions. We can first attempt to recover the analysis of [1], in which we “rediscover” the dilepton invariant mass distribution from LH slepton production and decay (now extracted via OSOF-SSOF subtraction, as above). The easiest way to do this in the presence of RH contamination is to focus on the OFOF channel. This reduces statistics by a factor of four, but leads to a signal which is much easier to interpret and compare to the dileptons.

We can further inquire into whether we can extract kinematic distributions involving the RH sleptons, which will occupy the SFOF and SFSF channels. There will be two main classes of RH events contributing, depending on where the third lepton comes from: either it is produced along with a LH slepton further down the chain, or it comes from the other side of the event.\textsuperscript{10} Since the flavor of the third lepton is uncorrelated in both cases, we cannot use this information to disentangle the two distributions. There is potentially a charge bias for leptons produced along with the LH sleptons in 3-body RH slepton decay, as pointed out in subsection II B. However, we also pointed out that it might be very difficult to spot. We therefore tentatively consider these two samples to be completely entangled.

This must then be added to the LH contribution. But, in principle, we can subtract out this contribution by utilizing its different flavor structure. OFOF is dominantly LH, and we can predict its contribution to the other channels using the 1:2:1 ratio above.

In particular, we can access the OSSF dilepton distribution embedded in the trilepton sample as follows. First, we construct the LH-dominated dilepton distribution in OFOF by making random pairings with the uniquely-signed lepton. This will contain equal amounts of correct pairings and incorrect pairings. Then we form the dilepton distribution in SFOF,

\textsuperscript{10} It may also come from the decay of the LH slepton further down the chain. This would require us to miss the lepton associated with the LH slepton production (lest the event end up classified as 4-lepton), as well as to pay the branching fraction price of 22%. These therefore represent a subdominant contribution.
using the unique OSSF pair. This will contain the distribution we are after, as well as
the LH contamination, also randomly paired due to the lack of flavor structure. Last, we
subtract off twice the distribution of OFOF. Assuming we have enough statistics to obtain
a meaningful final distribution, this can be checked against the OSSF excess found in the
dileptonic channels.

Using similar logic, we can try to access the trilepton invariant mass distribution from
RH slepton production and decay, with subsequent LH production in the same chain. The
precise shape of this distribution with all of the intermediate states on-shell was studied
in detail in [25]. It can serve as a useful supplement to the kinematic information already
available from the dilepton distributions. To maximize statistics, we take all trileptons from
the SFOF and SFSF channels (equivalently, all events in which we can find an OSSF pair),
and subtract from this three times the trilepton distribution of the OFOF events. This
will leave over the contribution of genuine correlated trileptons, all from the same chain,
but combined inextricably with the uncorrelated RH distribution. Of course, even if this
subtraction is too awkward to carry out due to limited statistics, or the purification ends up
being only modest due to the unsubtractable RH combinatorial background, we may still
simply plot the SFOF+SFSF distribution and look for a bump. For the samples which we
study in section IV at 100 fb$^{-1}$ luminosity, we take the latter tactic.

D. Flavor Non-Universal Signals from Left-Right Mixing

As we discussed in subsection II C, it is possible for otherwise flavor-blind spectra to
exhibit large differences between the decays of RH selectrons and RH smuons. The latter
can have non-negligible left-right mixing originating from the Yukawa couplings. This can
cause the RH smuons to dominantly decay via electroweak or Higgs boson emission, and
ultimately lose their muon-number to a sneutrino. The RH selectron, on the other hand,
would usually decay via neutralino emission, converting into an electron.

We can immediately infer the effects of these flavor non-universal decays on the dilepton
signals. The OSSF excess that would otherwise have been generated in RH smuon production
and decay will no longer exist. In principle, then, we could observe that the excess in OSSF
is entirely composed of electron pairs. Of course, the situation is not so simple, since we do
not know which pairs came from RH sleptons event-by-event. But we can still isolate the
presence of the excess by subtracting \(\text{OSSF}(e^+e^-) - \text{OSSF}(\mu^+\mu^-)\). This should practically equal the OSSF-OSOF distribution. A similar strategy was employed in [20], for spectra with lepton flavor violation in the SUSY soft terms (incorporating RH sneutrinos).

The RH smuon will not completely disappear from the dilepton channels, but its signatures will be highly attenuated and redistributed. Decays mostly proceed into \(W^{(*)}\bar{\nu}\), with the RH smuon acting like a LH smuon with a larger mass gap. In these decays, we get the usual 22% chance to generate a second lepton of opposite-sign but uncorrelated-flavor. We will therefore get a small enhancement of the OS excess, albeit at higher invariant mass than that caused by genuine LH sleptons. It will also be flavor-biased, consisting only of \(\mu\mu\) and \(\mu e\). Decays into \(Z^{(*)}\bar{l}_L\) and \(h^{(*)}\bar{l}_L\) can further contribute when the \(\bar{l}_L\) decays leptonically.\(^{11}\) Finding these signals may be relatively difficult without rather high statistics. To first approximation, we will consider the dileptonic signals of the RH smuons as lost.

The deficit of RH smuon decays will also manifest in the trilepton channels. The channels containing an OSSF pairing (SFOF+SFSF) will generally contain fewer muons. One way to see the effect is to simply plot the number of muons in these events. If the signals were perfectly flavor universal, the trilepton signal from RH sleptons would contain \((0\mu, 1\mu, 2\mu, 3\mu)\) in equal ratio. The signal from LH sleptons (with no flavor structure whatsoever) gets added in with ratio 1:3:3:1. We therefore expect, quite robustly, that completely flavor-blind chains will have equal amounts of \(0\mu\) and \(3\mu\), and equal amounts of \(1\mu\) and \(2\mu\). In the spectra with significant left-right mixing, the higher multiplicities are depleted, leading to biases \(0\mu > 3\mu\) and \(1\mu > 2\mu\).

Of course, it is also possible to have an intermediate case, where some non-dominant fraction of RH smuon decays go through electroweak channels. This would lead to smaller, but possibly still observable flavor biases.

We expect that similar kinds of electron-muon asymmetries can manifest in leptogenic SUSY [16]. Indeed, the possible importance of left-right mixing on (LH) smuon decays was also pointed out in that context, though there the muon counting was highly “contaminated” by misidentified stau CHAMPs. In similar scenarios with promptly-decaying stau NLSP, it may be possible to immediately observe an asymmetry between electrons and genuine muons. It would be interesting to study these effects in spectra similar to [15, 16] in more

\(^{11}\) A small fraction will also contribute to trilepton, when the \(Z\) decays leptonically.
FIG. 8: Important decay modes of the LH slepton in spectra with a light stau doublet. Note that the lepton flavor is correlated with its parent.

detail.

E. Signals with a Light Stau Doublet

If the mediation scale is relatively high, the LH stau doublet can be significantly pushed down in mass compared to the first two generations, due to Yukawa effects in the running of the soft masses. In particular, this occurs in the NUHM spectra of [12, 13]. We saw above, in subsection [II A], that splitting off the third generation can significantly change the decay modes of the LH sleptons of the first two generations, introducing sizable branching fractions into $l(\tilde{\nu}_\tau \nu_\tau)$ and $l(\tilde{\tau} \tau)$.

The relevant diagrams are illustrated in Fig. 8.

When dealing with these spectra, we shall revert to the assumption that RH sleptons are bypassed. Nonetheless, in some sense the LH sleptons of the first two generations take their place. The new decay modes now serve to populate an excess in the OSSF dilepton channel, in addition to the OS excess from the competing $W^*$ decay modes. The presence of these two overlapping excesses can be inferred, and their distributions separated, exactly as for the RH-active scenarios discussed above.

These spectra will also appear to be quite leptophilic. Tau production is now naturally quite high, and each tau has an approximately 35% chance of manifesting as an isolated electron or muon. In fact, since tau (and stau) decays proceed through $W^*$, we end up with several new opportunities for OS, flavor-uncorrelated dilepton signals. These signals

\footnote{Detailed analytic expressions can be found in [26]. Expressions for the case of a single neutralino dominating the decay can be found in our appendix, though we note that interference effects between Bino and Wino can be quite substantial, as the masses and couplings are in direct proportion in high-scale scenarios with unified gaugino mass. Decays into $\nu(\tilde{\nu}_\tau \nu_\tau)$ and $\nu(\tilde{\tau} \nu_\tau)$, via chargino exchange, will also be present, but they do not significantly change the phenomenology.}
will usually be biased towards low invariant mass, as the energy of the original tau must
be shared with two neutrinos. These new OS distributions will be irreversibly added on
top of the OS excess from the production and $W$-mediated decay of LH sleptons of the
first two generations.\(^{13}\) While the presence of this tau “contamination” actually increases
the leptonic rates, improves chances for discovery of a new physics signal, and moreover
indicates the presence of significant tau production through its shape, we see that it can
nonetheless obscure the physics we were originally interested in finding, namely the presence
of light LH sleptons decaying into sneutrinos. However, we will see that all of our signals
can in principle still be observed, even in the presence of this new SUSY background.

Naturally, the presence of taus in almost every event could be deduced by applying
hadronic tau tags. We expect that this will be a clear giveaway of the flavor (but not the
charge) of the NLSP, even if the tag is not very efficient. However, we will not rely on
hadronic taus for detailed kinematics. Instead we focus entirely on the performance of our
proposed multilepton measurements, which directly carry over from our RH-active analysis
and will be quite robust independent of the hadronic tau efficiency.

IV. COLLIDER SIMULATIONS

In order to determine what these signals might look like at the LHC, we have performed
simulations of three sample sneutrino NLSP spectra, along with Standard Model back-
grounds. The simulation and analysis methodology is identical to that in \([1]\). In particular,
we generate complete spectra, including radiative corrections, using SOFTSUSY \(v3.0.7\)\(^{27}\).
We generate SUSY $2 \rightarrow 2$ pair production using MadGraph/MadEvent \(v4.3.0\)\(^{28}\). We
use BRIDGE \(v2.17\)\(^{29}\) to calculate branching fractions and to simulate the decay chains.\(^{14}\)
We then shower and hadronize with PYTHIA \(v6.4.14\)\(^{30}\), and perform event reconstruction
with FastJet \(v2.3.4\)\(^{31}\). As before, we do not include detector effects beyond basic

\(^{13}\) In principle, we could determine whether a lepton is prompt, versus a product of tau decay, by mea-
suring the displacement of its track from the primary event vertex. However, the distribution of impact
parameters is quite broad, and depends on the unknown energy of the original tau. Separation of the
independent dilepton distributions with and without taus may not be feasible without high statistics and
careful analysis.

\(^{14}\) We use a modified version of BRIDGE which incorporates left-right mixing effects for the light generations.
We are grateful to Matt Reece for his help.
geometric acceptance and simple $p_T$ cuts on reconstruction.

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 used to keep more signal in events with high lepton multiplicity, namely three or more.) We set aside leptons which fail both of these criteria for clustering into jets.

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 $|\eta| < 2.5$.

We focus exclusively on super-QCD production modes, as these are the most spectacular, and the most straightforward to extract from the backgrounds. We require that each event have at least two jets with $p_T > 300$ GeV, and $E_T > 200$ GeV. We study events with at least one tight lepton, with the further requirement that a second lepton be tight in events with two or more leptons. These requirements very efficiently remove leptons from heavy flavor decay.

Backgrounds are as before, including $t\bar{t}$, single- and di-boson. $Z/\gamma$ are treated fully off-shell. We did not investigate new backgrounds relevant for 4-lepton and higher channels, as the 3-lepton backgrounds are already essentially negligible given our cuts on jet and $E_T$ activity.

Since many of our signals will require high luminosity to achieve good statistical control, we perform our analysis at 100 fb$^{-1}$. We optimistically assume that the LHC will be running at the design energy of 14 TeV by this point. A somewhat lower final operating energy will not significantly change our conclusions.

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15 Electroweak production of gauginos or RH sleptons may also yield very interesting multilepton signals, which may become especially relevant for a reduced energy LHC, or for searches at the Tevatron. We relegate the question of their observability for future studies.

16 The dominant 3-lepton background, with about 0.04 fb after cuts, is $WZ$+jets. We have included this in the analysis for illustration. The final sample has very low cross section per Monte Carlo event, and appears as a small contribution on 3-lepton plots (with fewer than one event per bin). $ZZ$+jets represents an even smaller contribution, and has not been included.
TABLE I: Physical masses (in units of GeV) in the three example spectra.

|            | RH-active | LR-mixed smuon | NUHM |
|------------|-----------|----------------|------|
| $\tilde{g}$ | 1403      | 1186           | 1034 |
| $\tilde{u}_L/\tilde{d}_L$ | 935 | 855 | 960 |
| $\tilde{u}_R$ | 944 | 878 | 863 |
| $\tilde{d}_R$ | 934 | 861 | 938 |
| $\tilde{t}_1$ | 866 | 801 | 672 |
| $\tilde{t}_2$ | 954 | 875 | 921 |
| $\tilde{b}_1$ | 912 | 824 | 881 |
| $\tilde{b}_2$ | 934 | 860 | 927 |
| $\tilde{\chi}^0_1$ | 285 | 360 | 182 |
| $\tilde{\chi}^0_2$ | 386 | 405 | 340 |
| $\tilde{\chi}^0_3$ | 458 | 425 | 544 |
| $\tilde{\chi}^0_4$ | 516 | 600 | 561 |
| $\tilde{\chi}^+_1$ | 384 | 390 | 341 |
| $\tilde{\chi}^+_2$ | 515 | 600 | 564 |
| $\tilde{e}_R$ | 254 | 316 | 408 |
| $\tilde{l}^+_L$ | 199 | 184 | 153 |
| $\tilde{\nu}$ | 184 | 166 | 131 |
| $\tilde{\nu}_\tau$ | 182 | 166 | 95 |
| $\tilde{\tau}_1$ | 198 | 174 | 120 |
| $\tilde{\tau}_2$ | 255 | 320 | 386 |

A. Simple RH-Active Spectrum

We start by analyzing a simple RH-active spectrum, where left-right mixing effects in the first two generations can be largely neglected, and electron-muon asymmetries are small. This spectrum was simulated using the assumptions of General Gauge Mediation, with a mediation scale of 100 TeV and $\tan \beta = 5$. The first column of table displays the physical mass spectrum. Since the Bino-like neutralino is relatively light (285 GeV) and there is no significant mass gap between LH and RH sleptons, RH smuons predominantly decay through
three-body neutralino-mediated processes.

The total leading-order SUSY production cross-section is 558 fb. Of this, 264 fb is super-QCD pair production, dominantly $\tilde{q}\tilde{q}^*$ and $\tilde{q}\tilde{q}$.

We first show the number of observed leptons (Fig. 9). As expected, the spectrum exhibits rich leptophilic behavior, with roughly 100 4-lepton events and handful of 5- and 6-lepton events.

The structure of the dileptonic and trileptonic channels is already very suggestive at the level of simple counting (Fig. 10). The dileptonic signal appears with OSSF>OSOF>SSSF=SSSF. The trileptonic channel includes a significant amount of OFOF events, which indicates the presence of OS, flavor-uncorrelated lepton pairs. Moreover, sum-
FIG. 11: (Simple RH-active spectrum.) Dilepton invariant mass distributions. The signal histograms are OSSF (black), OSOF (green), and averaged SS (red). The major backgrounds, averaged between OSSF and OSOF, are \( \tau \tau \) (cyan), dileptonic \( t\bar{t} \) (blue), and dileptonic \( WW \) (pink).

FIG. 12: (Simple RH-active spectrum.) Dilepton invariant mass distributions applying the OSSF-OSOF subtraction (left) and OSOF-SSOF subtraction (right). Backgrounds are included in the subtractions. The continuous gray histogram is background-only.

...ming the contents of OFOF and SFSF approximately matches the content of SFOF. This agrees with our expectations for RH-active spectra, as discussed in subsection III C.

We next analyze the dilepton invariant mass distributions using subtractions. We expect to see kinematic features from the following subcascades:

- \( \tilde{B}(\tilde{\chi}_1^0) \rightarrow \tilde{e}_R \rightarrow \tilde{\nu} \): a bump in the OSSF-OSOF subtraction with endpoint at 89 GeV (peak near 45 GeV),
FIG. 13: (Simple RH-active spectrum.) Dilepton invariant mass distribution within the OOF trilepton channel. We use the procedure described in [1] to reduce combinatorial ambiguities.

FIG. 14: (Simple RH-active spectrum.) Trileptonic invariant mass distribution of SFOF and SFSF leptons. On the right we show a theoretical prediction assuming that all three leptons are coming from the same decay chain, using a flat phase space generator. Note the different horizontal scales.

- $\tilde{B}(\tilde{\chi}_1^0) \rightarrow \tilde{l} \rightarrow \tilde{\nu}$: a bump in the OSOF-SSOF subtraction peaked at 40 GeV,
- $\tilde{W}^0(\tilde{\chi}_2^0) \rightarrow \tilde{l} \rightarrow \tilde{\nu}$: a bump in the OSOF-SSOF subtraction peaked at 60 GeV.

The dilepton invariant mass distributions in the different 2l channels (Fig. 11) indeed confirm that OSSF and OSOF dileptons have different shapes. Both are significantly above the SM backgrounds. Unfortunately, the expectation concerning the OSSF endpoint cannot be cleanly verified in this case since it falls in the bin surrounding the $Z$-mass, which has been intentionally blinded to avoid contamination from the possible SUSY production of
on-shell Zs. Nevertheless the shape of the distribution is clearly visible after subtraction (Fig. 12). Regarding the OSOF distribution, which is crucial evidence for sneutrino NLSP, we can clearly identify the first peak after subtraction (Fig. 12). The second peak, however, cannot be clearly distinguished. The first peak also materializes in the trileptonic OOF channel (Fig. 13), albeit with rather low statistics.

Finally, we look at the trilepton invariant mass of SFOF and SFSF dileptons (Fig. 14). If all three leptons were always coming from the same decay chain, corresponding to the process $\tilde{B} \rightarrow \tilde{e}_R \rightarrow \tilde{B}^* \rightarrow \tilde{l}$, they would reproduce, up to spin effects, the distribution depicted on the right side of Fig. 14. Although realistically we have combinatorial backgrounds, as well as backgrounds from LH chains (which we have not subtracted, due to limited statistics), we can still see clear evidence for the sharp spike. Observation of such a feature should motivate a more detailed kinematic analysis, which in this case is quite nontrivial. (However, see [25] for formulas applying to the case where the intermediate neutralino in $\tilde{e}_R$ decay is on-shell.)

B. RH-Active Spectrum with Flavor Non-Universal Signals due to Smuon Left-Right Mixing

We next analyze a spectrum where left-right mixing of the smuon leads to appreciably flavor non-universal signals. The physical spectrum appears in the second column of table I. The mass gap between the RH and LH sleptons is now large enough to allow for real emission of electroweak gauge bosons and Higgs bosons. This spectrum was again produced using General Gauge Mediation at a mediation scale of 100 TeV, and with $\tan \beta = 20$. The total leading-order SUSY cross section is 911 fb, of which 524 fb is from super-QCD pair production. SQCD production is again squark-dominated.

One additional noteworthy feature of this spectrum is that the neutralino mixing is not small, and the Bino is distributed nontrivially between the first and third neutralinos. Specifically, the gauge eigenstate composition of the lightest neutralino (360 GeV) is (36% $\tilde{B}$, 4% $\tilde{W}$, 33% $\tilde{H}_d$, 27% $\tilde{H}_u$), and of the third neutralino (64% $\tilde{B}$, 5% $\tilde{W}$, 15% $\tilde{H}_d$, 17% $\tilde{H}_u$).\footnote{The complete neutralino mixing matrix, with $(\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$ composition running horizontally and mass} This substantive mixing ultimately ends up having no qualitative impact on our analysis. Though there are now naively two Binos in the cascades, with RH squarks (of the first two...
generations) decaying 40/60% of the time into the first/third state, the subsequent decays of the lightest neutralino are highly biased towards invisible $\nu\bar{\nu}$ modes due to Wino-Bino interference combined with small phase space for $l\tilde{e}_R$. Effectively, then, there is only one Bino ($\tilde{\chi}_3^0$), and it is produced with a somewhat attenuated rate. This kind of situation is of course not required to achieve large electron-muon asymmetries, but it illustrates that our signals can actually be quite robust against neutralino mixing, despite the fact that most of our discussions above (and in [1]) used a simplified picture with pure gauge eigenstates.

We see from Figs. 15 and 16 that the lepton counting in this spectrum, neglecting detailed electron and muon composition, is similar to the simple RH-active spectrum. In the invariant mass distributions, we expect to see following kinematic features:

- $\tilde{B}(\tilde{\chi}_3^0) \rightarrow \tilde{e}_R \rightarrow \tilde{\nu}$: a bump in the OSSF-OSOF subtraction with endpoint at 147 GeV (peak near 75 GeV),
- $\tilde{B}(\tilde{\chi}_3^0) \rightarrow \tilde{l} \rightarrow \tilde{\nu}$: a bump in the OSOF-SSOF subtraction peaked at 65 GeV,
- $\tilde{W}^\nu(\tilde{\chi}_4^0) \rightarrow \tilde{l} \rightarrow \tilde{\nu}$: a bump in the OSOF-SSOF subtraction peaked at 120 GeV.

The first two of these predictions are indeed observed (Figs. 17 and 18), though statistics are somewhat limited.

The most striking new feature of this spectrum is the strong electron-muon asymmetry, originating from the very different decays of RH selectrons and RH smuons. While the former almost exclusively undergoes the usual 3-body decays mediated by off-shell neutralinos (contribution to the OSSF dilepton excess), the latter can mix into a LH smuon and emit an electroweak gauge boson, or emit a Higgs boson directly through the Yukawa coupling (subsection II C). Indeed, we find that 2-body electroweak modes account for approximately 95% of the decays of the RH smuon in this spectrum, with 63% going through $W$, and 16% each through $Z$ and $h$. We present simple counting measures of the asymmetry in dileptonic OSSF and trileptonic SFOF+SFSF in Fig. 19. We can clearly see a large mismatch between the number of $e^+e^-$ and $\mu^+\mu^-$ events contributing to the total (unsubtracted) OSSF sample,
without performing any more sophisticated analysis. In trilepton, we see the asymmetries $0\mu > 3\mu$ and $1\mu > 2\mu$ predicted in subsection III D.

We can also plot the difference between the dileptonic invariant mass distributions in the $e^+e^-$ and $\mu^+\mu^-$ channels (Fig. 20). While statistical fluctuations still limit a detailed comparison, the OSSF electron excess over OSSF muons is clearly consistent in shape and normalization with the total OSSF-OSOF excess.
FIG. 17: (LR-mixed smuon spectrum.) Dilepton invariant mass distributions. The signal histograms are OSSF (black), OSOF (green), and averaged SS (red). The major backgrounds, averaged between OSSF and OSOF, are \( \tau \tau \) (cyan), dileptonic \( t \bar{t} \) (blue), and dileptonic \( WW \) (pink).

FIG. 18: (LR-mixed smuon spectrum.) Dilepton invariant mass distributions applying the OSSF-OSOF subtraction (left) and OSOF-SSOF subtraction (right). Backgrounds are included in the subtractions. The continuous gray histogram is background-only.

C. Spectrum with a Light Stau Doublet - NUHM

Finally, we consider a spectrum with significantly lighter stau doublet, \( m(\tilde{\nu}_\tau) < m(\tilde{\tau}_L) < m(\tilde{\nu}_{e,\mu}) \). For this analysis, we use the second NUHM spectrum of [21], which arises from gaugino mediation [32, 33] with a large down-type Higgs mass at the mediation scale of
FIG. 19: (LR-mixed smuon spectrum.) Electron-muon counting in the dileptonic OSSF channel (left) and trileptonic SFOF+SFSF channels (right).

FIG. 20: (LR-mixed smuon spectrum.) Dilepton invariant mass distribution applying the $e^+e^- - \mu^+\mu^-$ subtraction. For comparison, the OSSF-OSOF subtraction is also displayed, as the continuous gray histogram (without error bars).

$2 \times 10^{16}$ GeV. The mass spectrum is displayed in the third column of table I.\(^\text{18}\) The total SUSY leading-order cross section is 4000 fb, with 1995 fb from super-QCD. The breakdown in terms of exclusive SQCD pairs is 111 fb $\tilde{g}\tilde{g}$, 937 fb $\tilde{g}\tilde{q}$, 357 fb $\tilde{q}\tilde{q}^*$, and 590 fb $\tilde{q}\bar{q}$.

We can again observe highly leptophilic behavior (Fig. 21), though the presence of OSSF

\(^{18}\) The detailed numerical values of the physical masses differ somewhat from those in [21]. Presumably, this can be accounted for by the fact that a different version of SOFTSUSY (namely 2.0.10) is used in that paper, or perhaps the input scale is slightly different. In any case, these small differences are largely irrelevant for our analysis.
production is now not so obvious from simple counting in sign/flavor channels (Fig. 22). Indeed, up to some small hint of flavor correlation, the latter appears quite consistent with the simplest sneutrino NLSP spectra. However, the high multiplicity is already a clear giveaway that there is more going on.

Much more can be inferred from the detailed invariant mass distributions. Given this spectrum, we expect to see following kinematic features in dileptons:

- $\tilde{B}(\tilde{\chi}^0_1) \rightarrow \tilde{l} \rightarrow \tilde{\nu}_\tau$: a bump in the OSSF-OSOF subtraction peaked near 77 GeV,
- $\tilde{W}^0(\tilde{\chi}^0_2) \rightarrow \tilde{l} \rightarrow \tilde{\nu}_\tau$: a bump in the OSSF-OSOF subtraction peaked near 115 GeV,
- $\tilde{B}(\tilde{\chi}^0_1) \rightarrow \tilde{l} \rightarrow \tilde{\nu}_{e,\mu}$: a bump in the OSOF-SSOF subtraction peaked at 25 GeV,
- $\tilde{W}^0(\tilde{\chi}^0_2) \rightarrow \tilde{l} \rightarrow \tilde{\nu}_{e,\mu}$: a bump in the OSOF-SSOF subtraction peaked at 75 GeV.

When we take the distributions (Fig. 23) and perform the subtractions (Fig. 24), we see distributions consistent with the presence of these features. But, as discussed in subsection III.E, there is also a significant OS contamination from leptonic tau decays. This appears in the right panel of Fig. 24 as a high rate in the lowest mass bin, representing an unresolved falling distribution. Disentangling this from the first slepton/sneutrino bump might be feasible with higher statistics, and the second bump is already almost well-resolved.

The presence of such nontrivial structures in the subtracted mass distribution is highly suggestive of the participation of sleptons and sneutrinos of the first two generations. However, the evidence is clearly not as clean compared to the cases without significant tau production.
FIG. 22: (NUHM spectrum.) Relative sign/flavor structure of the dileptonic and trileptonic channels. Histograms are stacked.

FIG. 23: (NUHM spectrum.) Dilepton invariant mass distributions. The signal histograms are OSSF (black), OSOF (green), and averaged SS (red). The major backgrounds, averaged between OSSF and OSOF, are $\tau\tau$ (cyan), dileptonic $t\bar{t}$ (blue), and dileptonic $WW$ (pink).

V. CONCLUSIONS AND OUTLOOK

In the present work, we have expanded our investigation of spectra with sneutrino NLSP to incorporate three simple variations which lead to very rich multilepton plus jets plus missing energy signals at the LHC. These include:

- spectra with $m(\tilde{e}_R) < m(\tilde{B}) < m(\tilde{q}), m(\tilde{g})$, such that there is an appreciable rate for decay chains that produce RH sleptons, with small effects from left-right mixing on the decays of the RH smuon,
The immediate signals of these spectra are high rates for multileptons, with reasonable chance to observe up to 6-lepton events in a 100 fb$^{-1}$ run of the LHC. Beyond this, we can identify some general features of the dileptonic and trileptonic invariant mass distributions, which allow us to extract kinematic information. Dileptons will contain independent excesses from the production/decay of both LH and RH sleptons, the former equally distributed between OSSF and OSOF channels, and the latter contained exclusively in OSSF. Together, these will appear as mismatched OSSF and OSOF excesses, from which we can extract the individual distributions by judicious subtractions. Backgrounds are non-negligible but in principle manageable. The same distributions will also exist in the trilepton channels, along with a potentially observable excess in the trilepton invariant mass. Here, the backgrounds are almost purely combinatorial and supersymmetric in origin.

In the spectra where electroweak decays dominate for the RH smuon, the multilepton signals can display substantial asymmetries between $e$ and $\mu$. If such signals were observed at the LHC, they might initially be interpreted as large flavor violation in the soft terms
of the first two generations, such as in [20]. Amusingly, though, these large effects on the flavor structure of the events actually originate directly from the ordinary electron and muon Yukawa couplings, appropriately supersymmetrized.

Spectra with a highly split-off stau doublet will look quite similar to more flavor-degenerate spectra with RH sleptons participating, though with a fairly prominent low-mass OS dilepton feature from leptonically decaying taus. This would be in addition to the fact that most events could be tagged with at least one hadronic tau.

We have seen that these three classes of spectra would be hard to miss at the LHC, and that they would support a large number of independent multilepton analyses. But, if we assume that such signals are supersymmetric in origin, how do we ultimately know that they are indicating the presence of a sneutrino NLSP? The irony of these scenarios is that while the high leptonic rates make them easy to discover, they also tend to obscure the detailed spectral structure in a pileup of overlapping signals from different sub-cascades. Still, the situation remains simple enough in the dileptonic and trileptonic channels to largely infer what is happening.

In our first paper, we advocated independent identification of a flavor-blind OS excess in the dileptonic invariant mass distributions within both the dilepton and trilepton channels. The trilepton analysis provided a powerful cross-check of the much more background-contaminated dileptonic analysis. We can still apply the same methodology here, but we must restrict ourselves to the OSOF channel since the OSSF contribution appears in superposition with the signal from the RH cascades. While it will no longer be straightforward to directly see that the OSOF signal is indeed half of a flavor-blind OS signal, this remains a very reasonable first assumption. In any case, as we have argued in [1], it does not seem straightforward to engineer such a large OSOF excess within the MSSM. Naively the easiest way to do this is to introduce a large population of OSSF taus from stau production and decay, and these will sometimes both decay into (flavor-uncorrelated) leptons. But this kind of scenario could be inferred in two ways: the invariant mass distribution would tend to be skewed towards lower masses due to the energy sharing with neutrinos, and there would necessarily be a high rate of hadronic tau production, which could be independently observed. We would therefore propose that the observation of the OSOF-SSOF signal with a well-localized invariant mass bump (or bumps), in combination with all of the other multileptonic activity, and with a modest rate for hadronic tau detection, makes the sneutrino
The NLSP interpretation is highly attractive.

Of course, arguing this case is more subtle for the NUHM-type spectra with light stau doublet, where genuine OS dileptons coexist with high production rates for taus. In fact, we saw there that the enhanced tau production directly led to a substantial contribution to OSOF. Still, there is hope that the prompt OSOF dileptons will have a distinct enough distribution to ultimately stand out against the low-mass tau shape. Even if this is not so clean, the complete set of signals would still be quite consistent with a tau-sneutrino NLSP.

In a broader context, it is clear that we have found some very distinctive new phenomenology within the MSSM. These signals have been largely overlooked in the past, partly because sneutrino NLSP spectra do not readily appear in canonical UV mediation scenarios, and partly because there has been little pressure to model-build from the dark matter perspective. However, there is obviously a benefit in exploring a more flexible approach to the MSSM, especially given our near-ignorance of physics beyond even a few hundred GeV. Conversely, should our signals be discovered in the coming years, they would indicate a SUSY mediation scenario quite distinct from what is typically imagined.

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Appendix A: Formulas for RH Slepton 3-Body Decay Widths

Here we present the 3-body decay widths for the RH sleptons via an intermediate off-shell Bino. These can become the dominant modes when the charginos and neutralinos are all heavier, so that 2-body modes $\tilde{e}_R^+ \rightarrow e_R^+ \tilde{\chi}^0$ (e.g., into mostly-Wino via gaugino mixing) are cut off. They will compete with the modes induced by left-right mixing, as discussed in subsection II C.

There are two types of 3-body processes: $\tilde{e}_R^+ \rightarrow e_R^+ l_L^+ \bar{l}_L$ proceeding via a chirality-
preserving $\tilde{B}$ propagator, and $\tilde{e}_R^+ \rightarrow e_R^+ l_L \tilde{l}_L^+$ proceeding via a chirality-flipping $\tilde{B}$ propagator. The general expressions for the widths of these decays depend on the three parameters $m_{\tilde{e}}$, $m_l$, and $m_{\tilde{B}}$, and are somewhat awkward. We also include the limits where $(m_{\tilde{e}} - m_l) \rightarrow 0$ or $m_l \rightarrow 0$, namely where the slepton is respectively nonrelativistic (NR) or ultrarelativistic (UR) in the $\tilde{e}_R$ rest frame. We also display the $m_{\tilde{B}} \gg m_{\tilde{e}}$ limit (non-propagating Bino) for the decays, since the expressions significantly simplify.

There are also the equivalent processes with $l$ replaced by $\nu$: $\tilde{e}_R^+ \rightarrow e_R^+ \nu \tilde{\nu}$ proceeding via a chirality-preserving $\tilde{B}$ propagator, and $\tilde{e}_R^+ \rightarrow e_R^+ \nu \tilde{\nu}^*$ proceeding via a chirality-flipping $\tilde{B}$ propagator. The expressions are identical, up to the obvious replacement $m_l \rightarrow m_{\tilde{\nu}}$.

We ignore gaugino mixing effects, treating the Bino as a pure mass state. Extending the formulas to a mixed neutralino is straightforward.

$g_1$ stands for the $U(1)_Y$ coupling ($g_1 \simeq 0.37$), and $Y_i$ stands for the hypercharge ($Y_{\tilde{e}} = 1$ and $Y_{\tilde{l}} = -1/2$).
$\Gamma(e_R^+ \to e_R^+ l_L^- \tilde{l}_L^-)$ (chirality-preserving): 

\[
\text{Full} = \frac{Y_{\ell e}^2}{2^3 \pi^3 m_B^3 m_e^3} \left[ m_B^2 (m_e^2 - m_{\tilde{f}}^2) (2 m_B^4 + 2 m_{\tilde{f}}^2 - m_B^2 (m_e^2 + m_{\tilde{f}}^2)) + 2 m_{\tilde{f}}^2 m_B^2 \log \left( \frac{m_B^2}{m_{\tilde{f}}^2} \right) + 2 (m_B^2 - m_{\tilde{f}}^2) \left( 3 m_B^2 + m_B^2 m_e^2 + m_B^2 m_{\tilde{f}}^2 - m_B^2 (4 m_B^2 + m_{\tilde{f}}^2) \right) \log \left( \frac{m_B^2}{m_{\tilde{f}}^2} \right) \right] + 3 \frac{m_B^2 - m_{\tilde{f}}^2}{m_B^2 - m_e^2} \left( (m_B^2 - m_{\tilde{f}}^2)^2 + 3(m_B^2 - m_e^2) m_B^2 (m_B^2 - m_{\tilde{f}}^2) \right) \log \left( \frac{1 + 2 m_e (m_B^2 - m_{\tilde{f}}^2)}{m_B^2 - m_{\tilde{f}}^2} \right)
\]

$\text{NR} = \frac{Y_{\ell e}^2}{3 \cdot 2^3 \pi^3 m_e^3} \left[ \frac{m_B^2}{m_e^2} - \frac{m_{\tilde{f}}^2}{m_e^2} \left( 3 \frac{m_B^2}{m_e^2} \log \left( 1 + 2 m_e m_e m_{\tilde{f}}^2 \right) \right) \left( \frac{m_B^2}{m_e^2} - \frac{m_{\tilde{f}}^2}{m_e^2} \right) \left( \frac{m_B^2}{m_e^2} - \frac{m_{\tilde{f}}^2}{m_e^2} \right) \log \left( 1 + 2 m_e \frac{m_B^2}{m_e^2} \right) \right]$

$\text{UR} = \frac{Y_{\ell e}^2}{3 \cdot 2^3 \pi^3 m_e^3} \left[ \frac{m_B^2}{m_e^2} - 5 + 2 \left( 3 \frac{m_B^2}{m_e^2} - 4 \frac{m_B^2}{m_e^2} + 1 \right) \log \left( 1 - \frac{m_{\tilde{f}}^2}{m_B^2} \right) \right]$

$\Gamma(e_R^+ \to e_R^+ l_L^- \tilde{l}_L^-)$ (chirality-flipping): 

\[
\text{Full} = \frac{Y_{\ell e}^2}{2^3 \pi^3 m_B^3 m_e^3} \left[ m_B^2 (m_e^2 - m_{\tilde{f}}^2) (2 m_B^4 + 2 m_{\tilde{f}}^2 - m_B^2 (m_e^2 + m_{\tilde{f}}^2)) + 2 m_{\tilde{f}}^2 m_B^2 \log \left( \frac{m_B^2}{m_{\tilde{f}}^2} \right) + 2 (m_B^2 - m_{\tilde{f}}^2) \left( (m_B^2 - m_{\tilde{f}}^2)^2 + 3(m_B^2 - m_e^2) m_B^2 (m_B^2 - m_{\tilde{f}}^2) \right) \log \left( \frac{1 + 2 m_e (m_B^2 - m_{\tilde{f}}^2)}{m_B^2 - m_{\tilde{f}}^2} \right) \right] + 3 \frac{m_B^2 - m_{\tilde{f}}^2}{m_B^2 - m_e^2} \left( (m_B^2 - m_{\tilde{f}}^2)^2 + 3(m_B^2 - m_e^2) m_B^2 (m_B^2 - m_{\tilde{f}}^2) \right) \log \left( \frac{1 + 2 m_e \frac{m_B^2}{m_e^2}}{m_B^2 - m_{\tilde{f}}^2} \right)
\]

$\text{NR} = \frac{Y_{\ell e}^2}{m_e^3} \Gamma(e_R^+ \to e_R^+ l_L^- \tilde{l}_L^-)_{\text{NR}}$

$\text{UR} = \frac{Y_{\ell e}^2}{2^3 \pi^3 m_e^3} \left[ 2 - \frac{m_{\tilde{f}}^2}{m_B^2} + 2 \left( \frac{m_B^2}{m_e^2} - 1 \right) \log \left( 1 - \frac{m_{\tilde{f}}^2}{m_B^2} \right) \right]$

$\to \frac{Y_{\ell e}^2}{3 \cdot 2^3 \pi^3 m_B^3} \left[ \frac{m_B^2}{m_e^2} - 5 + 2 \left( 3 \frac{m_B^2}{m_e^2} - 4 \frac{m_B^2}{m_e^2} + 1 \right) \log \left( 1 - \frac{m_{\tilde{f}}^2}{m_B^2} \right) \right]$
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