Natural SUSY at LHC with Right Sneutrino LSP

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Abstract: We study an extension of the minimal supersymmetric standard model (MSSM) with additional right-handed singlet neutrino superfields. While such an extension incorporates a mechanism for the neutrino mass, it also opens up the possibility of having the right-sneutrinos ($\tilde{\nu}$) as the lightest supersymmetric particle (LSP). In this work, we focus on the the viability of rather small ($\lesssim 500$ GeV) higgsino mass parameter ($\mu$), an important ingredient for “naturalness”, in the presence of such a LSP. For simplicity, we assume that the bino and wino mass parameters are much heavier; thus we only consider (almost) pure and compressed higgsino-like states, with small $\mathcal{O}(10^{-2})$ gaugino admixture. Considering only prompt decays of the higgsino-like states, especially the lightest chargino, we discuss the importance of leptonic channels consisting of up to two leptons with large missing transverse energy to probe this scenario at the Large Hadron Collider (LHC). Further, we emphasize on how the gaugino mass parameters, although very heavy, affects the decay of the low-lying higgsino-like states, thus significantly affecting the proposed signatures at LHC.

Keywords: Supersymmetric Phenomenology, Natural Supersymmetry, Right sneutrino Dark Matter
1 Introduction

The TeV scale limits from LHC searches on the masses of strongly interacting supersymmetric particles set a dismal tone for naturalness concerns, a prime motivation for invoking Supersymmetry (SUSY) in particle physics studies. While several studies in the literature attempt to quantify “naturalness” in a supersymmetric scenario, the interpretation and the measure of naturalness are often debated [1–6]. Nevertheless, a small value of the Higgsino mass parameter $\mu$ and possibly rather light stop squarks and gluinos remain desirable in “natural” scenarios at the electro-weak (EW) scale [5–10].

While the constraints on stop squarks and gluinos are rather stringent due to their large production cross-section at the LHC, the weakly interacting sector with
rather light electroweakinos in general, and higgsinos in particular, remain viable [11, 12]. There have been several analyses on light electroweakinos, assuming a simplified spectra with one or more specific decay channels [13–21]. Further, the constraints on the mass of the light higgsino-like states have been studied in detail because of their importance in a “natural” supersymmetric scenario [22–27]. However, note that these analyses assume the lightest neutralino as the lightest supersymmetric particle (LSP). In scenarios with conserved R-parity, the search strategies, and therefore the limits of various sparticle masses, depend on the nature of the LSP. This is because in such scenarios the LSP appears at the end of the decay chain of each sparticle, therefore dictating the possible search channels. This warrants investigation of supersymmetric scenarios with different types of LSP. While within the paradigm of the MSSM, the lightest neutralino is the LSP, and most supersymmetric searches are based on the same assumption. There has been studies with gravitino LSP, discussing implications on cosmology and signatures at the LHC [28–49]. In other simple extensions, axion and/or axino as the LSP [50–54] and even sneutrino LSP have also been considered [55–71]. While the former sets out to resolve the strong CP-problem, the latter provides a weak-scale solution to the neutrino mass generation issue, an important aspect missing in the MSSM.

In this work we consider a similar extension to the MSSM with three generations of right-neutrino superfields. This scenario, which provides a weak-scale solution to the neutrino mass generation issue, has been widely studied in supersymmetric extensions. While the left-sneutrinos have been ruled out as a DM candidate long ago, thanks to the stringent limit from direct detection experiments [72], right-sneutrinos continue to be widely studied as a candidate for DM in extended frameworks of the MSSM [55–66, 69, 73–75]. In its simplest incarnation as ours, the right-sneutrinos at EW scale remain very weakly interacting, thanks to the small Yukawa coupling \( \mathcal{O}(10^{-6} - 10^{-7}) \) determining their coupling strength to other particles. However, as in the case of the charged sfermions where the tri-linear soft-supersymmetry breaking parameters \( \mathcal{A}_i \) are responsible for inducing left-right admixtures in the mass eigenstates, a rather large value in the right-sneutrino case will induce significant left-admixture and therefore substantially increase the interaction strengths [63, 64, 73]. In both of these scenarios, DM aspects as well as search strategies at LHC have been studied for certain choices of the SUSY spectra [76–81].

We note that in the light of “naturalness”, it becomes equally important to investigate the supersymmetric spectrum in such a scenario. In particular we focus on a minimalistic spectrum, motivated by “naturalness” at the EW scale, with light higgsino-like states and a right-sneutrino LSP. However, the third generation squarks and gluinos will be beyond the scope of the present work and will be addressed in a subsequent extension. So the strongly interacting sector of the sparticles is assumed to be very heavy along with the choice that the gaugino mass parameters are also large enough \( \gtrsim \mathcal{O}(1) \text{ TeV} \) to ensure that the light electroweakinos are
higgsino-dominated states. Note that the presence of a mixed right-sneutrino as the LSP will lead to a very different signature even from the compressed higgsino-like states, mostly due to the leptonic decay of the light chargino. Although leptonic channels provide a cleaner environment for new physics searches at a hadron machine such as the LHC, one expects that the level of compression in the mass spectra of the electroweakinos would also play a major role in determining the efficacy of the leptonic channels. We investigate the prospects of discovery of such channels at the 13 TeV run of LHC. As the gaugino mass parameters have been assumed to be too large, the production cross-section for gaugino-like neutralinos and charginos at the LHC would be hardly significant. However the gaugino parameters are still found to be relevant through their mixing with the light higgsino-like states. At tree-level the mixing with the gaugino-like states, even though very small ($\mathcal{O}(10^{-2})$) affects the hierarchy as well as the mass difference of the three light higgsino-like states. In addition, these parameters significantly affect the decay properties of the higgsino-like states which in turn determines the branching fractions of the different decay modes of the light higgsino-like states. We also note that depending on the neutrino Yukawa coupling and the amount of left-right mixing in the sneutrino sector in general, the collider signatures for the electroweakinos strongly depend on the relative sign and magnitude of gaugino mass parameters.

The article is organized as follows. In Section 2 we discuss the model and the underlying particle spectrum of interest in detail. In the following Section 3 we focus on identifying the parameter space satisfying relevant constraints as well as implications on neutrino sector and a sneutrino as DM. In Section 4 we discuss the possible signatures at LHC and present our analysis for a few representative points in the model parameter space. We finally conclude in Section 5.

2 The Model

We consider an extension to the Minimal Supersymmetric Standard Model (MSSM) by introducing a right-chiral neutrino superfield for each generation. This extension addresses the important issue of neutrino mass generation which is otherwise absent in the MSSM. In particular, we adopt a phenomenological approach for “TeV type-I seesaw mechanism”. The superpotential, suppressing the generation indices, is given by [55, 73, 82]:

$$W \supset W_{\text{MSSM}} + y_\nu \hat{L} \hat{H}_u \hat{N}^c + \frac{1}{2} M_R \hat{N}^c \hat{N}^c$$

where $y_\nu$ is the neutrino Yukawa coupling, $\hat{L}$ is the left-chiral lepton doublet superfield, $\hat{H}_u$ is the Higgs up-type chiral superfield and $\hat{N}$ is the right-chiral neutrino superfield. Besides the usual MSSM superpotential terms denoted by $W_{\text{MSSM}}$, we now have an added Yukawa interaction term involving the left-chiral superfield $\hat{L}$.
coupled to the up-type Higgs superfield $\tilde{H}_u$, and $\tilde{N}$. SM neutrinos obtain a Dirac mass $m_D$ after electroweak symmetry breaking once the neutral Higgs field obtains a vacuum expectation value ($v_Y$) $v_u$, such that $m_D = y_\nu v_u$. The third term $\frac{1}{2} M_R \tilde{N}^c \tilde{N}^c$ is a lepton-number violating ($\Delta L = 2$) term.

In addition to the MSSM contributions, the soft-supersymmetry breaking scalar potential receives additional contributions as follows:

$$\mathcal{V}_{\text{soft}} \supset \mathcal{V}_{\text{MSSM}} + m_R^2 |\tilde{N}|^2 + \frac{1}{2} B_M \tilde{N}^c \tilde{N}^c + (T_\nu \tilde{L} H_u \tilde{N}^c + \text{h.c.})$$

where $m_R^2$ is the soft-supersymmetry breaking mass parameter for the sneutrino, $B_M$ is the soft mass-squared parameter corresponding to the lepton-number violating term and $T_\nu$ is the soft-supersymmetry breaking L-R mixing term in the sneutrino sector. We have suppressed the generation indices both for the superpotential as well as for the soft supersymmetry-breaking terms so far.

Note that a small $\mu$-parameter is critical to ensure the absence of any fine-tuning at the EW scale ($\Delta_{\text{EW}}$) [5–8]. Fine-tuning arises if there is any large cancellation involved at the EW scale in the right hand side of the following relation [1, 2] :

$$\frac{M_Z^2}{2} = \frac{m_{H_u}^2 + \Sigma_d}{\tan \beta^2 - 1} - \mu^2,$$

where $m_{H_u}^2$, $m_{H_d}^2$ denote the soft-supersymmetry breaking terms for the up-type and the down-type Higgses at the supersymmetry breaking mass scale (which is assumed to be the geometric mean of the stop masses in the present context) and $\tan \beta$ denotes the ratio of the respective vevs while $\Sigma_u$ and $\Sigma_d$ denote the radiative corrections. Note that, since we are not considering any specific high-scale framework in the present context, we are only concerned about the EW fine-tuning. Typically $\Delta_{\text{EW}} \lesssim 30$ is achieved with $|\mu| \lesssim 300$ GeV [5–8]. The assurance of EW naturalness is the prime motivation in exploring small $\mu$ scenarios. However it is quite possible that obtaining such a spectrum from a high-scale theory may require larger fine-tuning among the high-scale parameters and/or the logarithmic running involved, especially considering that $m_{H_u}$ evolves significantly to ensure radiative EW symmetry breaking. Therefore, $\Delta_{\text{EW}}$ can be interpreted as a lower bound on fine-tuning measure [5–8]. Note that, stop squarks and gluinos contribute to the radiative corrections to $m_{H_u}$ at one and two-loop levels respectively. It has been argued [9, 10] that an EW fine-tuning of less than about 30 can be achieved with $\mu \lesssim 300$ GeV and with stop squarks and (gluinos) as heavy as about 3 TeV (4 TeV). It is, therefore, important to probe possible scenarios with low $\Delta_{\text{EW}}$ and therefore with low $|\mu|$.

2.1 The (s)neutrino sector

In presence of the soft-supersymmetry-breaking terms $B_M$, a split is generated between the CP-even and the CP-odd part of right-type sneutrino fields. In terms of
CP eigenstates we can write: \( \tilde{\nu}_L = \frac{\tilde{\nu}_e + i \tilde{\nu}_o}{\sqrt{2}} \), \( \tilde{\nu}_R = \frac{\tilde{\nu}_e - i \tilde{\nu}_o}{\sqrt{2}} \), where superscripts \( e, o \) denote “even” and “odd” respectively. The sneutrino (\( \tilde{\nu} \)) mass-squared matrices in the basis \( \tilde{\nu}^e = \{ \tilde{\nu}^e_L, \tilde{\nu}^e_R \}^T \) and \( \tilde{\nu}^o = \{ \tilde{\nu}^o_L, \tilde{\nu}^o_R \}^T \) are given by,

\[
\mathcal{M}^2 = \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{LR}^2 & m_{RR}^2 \end{pmatrix},
\]

where,

\[
m_{LL}^2 = m_L^2 + \frac{1}{2} m_Z^2 \cos 2\beta + m_D^2,
\]

\[
m_{LR}^2 = (T_{\nu} \pm y_{\nu} M_R) v \sin \beta - \mu m_D \cot \beta,
\]

\[
m_{RR}^2 = m_R^2 + m_D^2 + M_R^2 \pm B_M,
\]

with \( j \in \{ e, o \} \) and the ‘+’ and the ‘-’ signs correspond to \( j = e \) and \( j = o \) respectively, and \( v = \sqrt{v_u^2 + v_d^2} = 174 \text{ GeV} \), where \( v_u, v_d \) denotes the vevs of the up-type and the down-type CP-even neutral Higgs bosons. Further, we have assumed \( T_{\nu} \) to be real and with no additional CP-violating parameters in the sneutrino sector. The physical masses and the mass eigenstates can be obtained by diagonalizing these matrices. The eigenvalues are given by :

\[
m_{1,2}^2 = \frac{1}{2} \left( m_{LL}^2 + m_{RR}^2 \pm \sqrt{(m_{LL}^2 - m_{RR}^2)^2 + 4 m_{LR}^4} \right).
\]

The corresponding mass eigenstates are give by,

\[
\tilde{\nu}_1 = \cos \varphi \tilde{\nu}^i_L - \sin \varphi \tilde{\nu}^i_R
\]

\[
\tilde{\nu}_2 = \sin \varphi \tilde{\nu}^i_L + \cos \varphi \tilde{\nu}^i_R.
\]

The mixing angle \( \theta = \frac{\pi}{2} - \varphi \) is given by,

\[
\sin 2\theta^j = \frac{(T_{\nu} \pm y_{\nu} M_R) v \sin \beta - \mu m_D \cot \beta}{m_{1}^2 - m_{1}^2},
\]

where \( j \) denotes CP-even (\( e \)) or CP-odd (\( o \)) states.

The off-diagonal term involving \( T_{\nu} \) is typically proportional to the coupling \( y_{\nu} \), ensuring that the left-right (L-R) mixing is small. However, the above assumption relies on the mechanism of supersymmetry-breaking and may be relaxed. The phenomenological choice of a large \( T_{\nu} \sim O(1) \text{GeV} \) leads to increased mixing between the left and right components of the sneutrino flavor eigenstates in the sneutrino mass eigenstates \([63, 64, 73] \). Further, if the denominator in eq. (2.5) is suitably small, it can also lead to enhanced mixing.
As for the neutrinos, at tree-level with $M_R \gg 1$ eV, their masses are given by

$$m_\nu \simeq \frac{y_\nu^2 v_u^2}{M_R}$$

as in the case of Type-I see-saw mechanism [83–85]. Thus, with $M_R \sim O(100)$ GeV, neutrino masses of $O(0.1)$ eV requires $y_\nu \sim 10^{-6} - 10^{-7}$. Although we have ignored the flavor indices in the above discussion of the sneutrino sector, the neutrino oscillation experiments indicate that these will play an important role in the neutrino sector. We will assume that the leptonic Yukawa couplings are flavor diagonal, and that the only source of flavor mixing arises from $y_\nu$ [86]; see also [87, 88].

![Figure 2.1](image.png)

Figure 2.1. Schematic diagram showing the leading one-loop contribution to the light neutrino mass.

Further, at one-loop, flavor diagonal $B_M$ can also contribute to the neutrino mass matrix [82, 89] which can be quite significant in the presence of large $T_\nu$ in particular. The dominant contribution to the Majorana mass of the active neutrino arises from the sneutrino-gaugino loop as shown in fig. 2.1. The contributions from the loop are proportional to the mass splitting between the CP-even and the CP-odd left-sneutrino state which makes it significant in the presence of a rather large $T_\nu$ which is responsible for left-right mixing in the sneutrino sector (see eq. 2.5). These additional contributions to the neutrino mass give significant constraints in the $\{T_\nu, B_M\}$ parameter space. We shall discuss this in more detail in Section 3.\footnote{Note that flavor off-diagonal terms in $B_M$ can lead to flavor mixing in the neutrino sector via higher order effects which we avoid in our discussions for simplicity.}

Finally, some comments on the scenario with $M_R = 0$ and $B_M = 0$ are in order. With $M_R = 0$ (and $B_M = 0$), only Dirac mass terms would be present for neutrinos, which is given by $y_\nu v_u$. The oscillation data for neutrinos can only be satisfied by assuming $y_\nu$ (and/or $T_\nu$, at one-loop order) to be flavor off-diagonal. In addition, $O(0.1)$ eV neutrino mass, then, requires a very small $y_\nu \simeq 10^{-11}$.

In the sneutrino sector, the relevant mass eigenstates may be obtained simply by substituting $M_R = 0 = B_M$ in equations (2.1, 2.2, 2.3). Since the mass matrices for both CP-even and the CP-odd sneutrinos are identical in this scenario, any splitting between the corresponding mass eigenstates would be absent. Consequently there
will be only two complex-scalar mass eigenstates $\tilde{\nu}_1, \tilde{\nu}_2$. Also, there will be no large one-loop contribution to the Majorana neutrino mass, relaxing the constraint on large $T_\nu$ significantly.

2.2 The Electroweakino sector

The other relevant sector for our study is the chargino-neutralino sector, in particular the higgsino-like states. This sector resembles the chargino-neutralino sector of the MSSM. The tree-level mass term for the charginos, in the gauge eigen-basis, can be written as [90]

$$-\mathcal{L}_{\text{mass}}^c = \psi^{-T} M^c \psi^+ + h.c. \quad (2.6)$$

where,

$$\psi^+ = (\tilde{W}^+, \tilde{h}^+), \quad \psi^- = (\tilde{W}^-, \tilde{h}^-)^T \quad (2.7)$$

are column vectors whose components are Weyl spinors. The mass matrix $M^c$ is given by

$$M^c = \left( \begin{array}{cc} M_2 \sqrt{2} M_W \sin \beta & \mu \\ \sqrt{2} M_W \cos \beta \end{array} \right). \quad (2.8)$$

In the above equation, $M_2$ is the supersymmetry breaking $SU(2)$ gaugino (wino) mass parameter, $\mu$ is the supersymmetric higgsino mass parameter, $M_W$ is the mass of the $W$ boson, and $\tan \beta$ is the ratio of vevs as described before. The non-symmetric $M^c$ can be diagonalized with a bi-unitary transformation using the unitary matrices $U$ and $V$ to obtain the diagonal mass matrix,

$$M^c_D = U^* M^c V^{-1} = \text{Diagonal}(m_{\tilde{\chi}^+_1}, m_{\tilde{\chi}^+_2}). \quad (2.9)$$

The eigenstates are ordered in mass such that $m_{\tilde{\chi}^+_1} \leq m_{\tilde{\chi}^+_2}$. The left- and right-handed components of the corresponding Dirac mass eigenstates, the charginos $\tilde{\chi}^+_i$ with $i \in \{1, 2\}$, are

$$P_L \tilde{\chi}^+_i = V_{ij} \psi^+_j, \quad P_R \tilde{\chi}^+_i = U^*_{ij} \psi^-_j, \quad (2.10)$$

where $P_L$ and $P_R$ are the usual projectors, $\psi^-_j = \psi^{\dagger}_j$, and summation over $j$ is implied.

For the electrically neutral neutralino states, in the gauge eigenbasis, $\psi^0 = \left( \tilde{B}^0, \tilde{W}^0, \tilde{h}^0_1, \tilde{h}^0_2 \right)^T$, the tree level mass term is given by [90]

$$-\mathcal{L}_{\text{mass}}^n = \frac{1}{2} \psi^{0T} M^n \psi^0 + h.c. \quad (2.11)$$

The neutralino mass matrix $M^n$ can be written as

$$M^n = \left( \begin{array}{cccc} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{array} \right). \quad (2.12)$$

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In the above mass matrix $s_W, s_\beta, c_W$ and $c_\beta$ stand for $\sin \theta_W,\sin \beta,\cos \theta_W$ and $\cos \beta$ respectively while $\theta_W$ is the weak mixing angle. $M_Z$ is the mass of the $Z$ boson, and $M_1$ is the supersymmetry breaking $U(1)_Y$ gaugino (bino) mass parameter. $M^n$ can be diagonalized by a unitary matrix $N$ to obtain the masses of the neutralinos as follows,

$$M^n_D = N^\dagger M^n N^{-1} = \text{Diagonal}(m_{\tilde{\chi}^0_1} \ m_{\tilde{\chi}^0_2} \ m_{\tilde{\chi}^0_3} \ m_{\tilde{\chi}^0_4})$$

(2.13)

Again, without loss of generality, we order the eigenvalues such that $m_{\tilde{\chi}^0_1} \leq m_{\tilde{\chi}^0_2} \leq m_{\tilde{\chi}^0_3} \leq m_{\tilde{\chi}^0_4}$.

The left–handed components of the corresponding mass eigenstates, described by four–component Majorana neutralinos $\tilde{\chi}^0_i$ with $i \in \{1, 2, 3, 4\}$, may be obtained as,

$$P_{L\tilde{\chi}^0_i} = N_{ij} \psi^0_j,$$

(2.14)

where summation over $j$ is again implied; the right–handed components of the neutralinos are determined by the Majorana condition $\tilde{\chi}^{c}_i = \tilde{\chi}^0_i$, where the superscript $c$ stands for charge conjugation.

Since the gaugino mass parameters do not affect “naturalness”, for simplicity we have assumed $M_1, M_2 \gg |\mu|$. In this simple scenario there are only three low-lying higgsino-like states, $\tilde{\chi}^0_1, \tilde{\chi}^0_2$ and $\tilde{\chi}^0_\pm$. The EW symmetry breaking induces mixing between the gaugino and the higgsino-like states, via the terms proportional to $M_Z, M_W$ in the mass matrices above. The contributions of the right-chiral neutrino superfields to the chargino and neutralino mass matrices are negligible, thanks to the smallness of $y_\nu (\simeq 10^{-6})$. Thus lightest neutralino and charginos are expected to be nearly the same as in the MSSM. Following [91] (see also [92]), in the limit $M_1, M_2 \gg |\mu|$, we give the analytical expression for the masses below,

$$m_{\tilde{\chi}^\pm_i} = |\mu| \left(1 - \frac{M_W^2 \sin 2\beta}{\mu M_2}\right) + \mathcal{O}(M_2^{-2}) + \text{rad.corr.}$$

$$m_{\tilde{\chi}^{a,s}_i} = \pm \mu - \frac{M_Z^2}{2} (1 \pm \sin 2\beta) \left(\frac{\sin \theta_W^2}{M_1} + \frac{\cos \theta_W^2}{M_2}\right) + \text{rad.corr.}$$

(2.15)

where the subscripts $s \ (a)$ denote symmetric (anti-symmetric) states respectively, and the sign of the eigenvalues have been retained. For the symmetric state $N_{i3}, N_{i4}$ share the same sign, while for the anti-symmetric state there is a relative sign between these two terms. Although the leading contribution to the mass eigenvalues are given by $|\mu|$ (which receives different radiative corrections in $M^n$ and $M^c$), $M_1, M_2$ and tan $\beta$ affects the mass splitting between the three light higgsino-like states due to non-negligible gaugino-higgsino mixing. The radiative corrections, mostly from the third generation (s)quarks, contribute differently for $m_{\tilde{\chi}^\pm_i}$ and $m_{\tilde{\chi}^{a,s}_i}$ and have been estimated in [91, 93–95]. As we are interested in a spectrum where the lighter chargino and the neutralinos play a major role and the knowledge of their mass differences would become crucial, it is necessary to explore what role the relevant
SUSY parameters have in contributing to the masses of the higgsino dominated states. It is quite evident from our choice of large $M_1$ and $M_2$ that the three states according to eq. 2.15 would be closely spaced. We now look at how the variation of the the above gaugino parameters affect the shift in mass of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_{1,2}^0}$.

Figure 2.2. The left (right ) panel shows the variation of the mass difference $\Delta m_1 = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ ($\Delta m_2 = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^\pm}$) between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ ($\tilde{\chi}_2^0$) for $\tan \beta = 5$ with respect to $M_1$, with $M_2$ on the palette.

Assuming $\mu = 300$ GeV, $\tan \beta = 5$, in fig. 2.2 we show the variation of the mass differences $\Delta m_1 = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and $\Delta m_2 = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^\pm}$ as a function of the gaugino mass parameters. $M_1$ and $M_2$ have been varied from 500 GeV to 3 TeV. Further, we have set $M_3 = 2$ TeV.

We have used SARAH [96, 97] to generate model files for SPheno [98, 99], and have used the same to estimate the masses. Since SLHA [100] convention has been followed, the input parameters, as shown in the figures above, are interpreted as DR parameters at ~ 1.6 TeV. Note that the same model and spectrum generators have been used for all subsequent figures.
The following features are noteworthy from figure 2.2:

• For positive $\mu$ and $M_1, M_2 \gg \mu$, the anti-symmetric state with positive eigenvalue is $\tilde{\chi}_0^0$, while $\tilde{\chi}_2^0$ is the symmetric state with negative eigenvalue. The anti-symmetric state has larger gaugino fraction in most parameter space. This remains the lightest higgsino-like state in the entire region of the parameter space, as indicated by a smoothly varying $\Delta m_1$ in fig. 2.2(a). Also, since $\tilde{\chi}_2^0$ has very little gaugino-admixture, it is the heaviest higgsino-like state in this region, while $\tilde{\chi}_1^\pm$ remains between the two neutralinos.

For a fixed $M_1 \gg |\mu|$, the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_0^0$ increases as $M_2$ decreases. This feature can be understood by looking at eq. 2.15 which implies that with increasing $M_2$, $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_0^0}$ both approach $\mu$ while their separation $\Delta m_1$ decreases since it includes a positive contribution proportional to $1/M_2$. A similar conclusion can be made for $\Delta m_2$. As $M_2$ becomes smaller, the the wino component in $\tilde{\chi}_0^0$ and $\tilde{\chi}_1^\pm$ increases and both of these states are pushed down. However, the symmetric state $\tilde{\chi}_2^0$ is not affected. Consequently the variation in $\Delta m_2$ is larger compared to $\Delta m_1$ in this case.

• For positive $\mu$ and negative $M_1$, the anti-symmetric state with positive eigenvalue remains the lightest for most of the parameter space. This state also has rather large gaugino admixture in most of the parameter space, as in the previous case. However, for negative $M_1$ the bino-like state also corresponds to a negative eigenvalue state, and mixes well with the negative eigenvalue (symmetric) higgsino-like state, while the anti-symmetric higgsino-like state mixes dominantly with the wino-like state and its bino admixture is smaller compared to the positive $M_1$ scenario described above. Thus, smaller gaugino admixture to the anti-symmetric state can lead to negative $\Delta m_1$, since the lightest chargino can become lighter than this state in spite of the larger electro-magnetic radiative contribution it receives for a wide range of $M_2$ [23, 24, 32]. Note that the larger off-diagonal term in the chargino mass matrix ensures larger higgsino-wino mixing. For large $M_2$ values ($\gtrsim$ 2 TeV), the region $|M_1| \lesssim 1$ TeV, as shown in fig.2.2(a), such a scenario manifests itself.

Further, for $|M_1| \ll M_2$, bino-higgsino mixing in the symmetric higgsino-like state can be large and the state is pushed down to become the lightest neutralino state. Thus, in this region the switch in the nature of the lightest neutralino state leads to an upward kink in the $\Delta m_1$ and $\Delta m_2$ plots, as shown in figs. 2.2(a) and 2.2(b).

\footnote{Although our numerical analysis, as shown in figure 2.2, includes radiative corrections, the generic features also appear at the tree-level for $|\mu| = 300$ GeV, $M_1, M_2 \gg |\mu|$ and $\tan \beta = 5$. We have checked this using a Mathematica code.}
• For negative $\mu$, the situation is somewhat different. In this case the symmetric state corresponds to the positive eigenvalue and the anti-symmetric state corresponds to the negative eigenvalue. As in the case of positive $\mu$, the anti-symmetric state has larger gaugino fraction in most of the parameter space. For positive $M_1$, the positive eigenvalue (symmetric) state remains the lightest neutralino, while the anti-symmetric state remains the heaviest higgsino-like state, as can be inferred from eq. 2.15. As shown in figs. 2.2(c) and 2.2(d), similar to the positive $\mu$ case, $\Delta m_i$ smoothly increases with decreasing $M_2$ in this region as well.

• For negative $\mu$ and negative $M_1$, the symmetric state with positive eigenvalue remains the lightest higgsino-like state in most parameter space, similar to the positive $M_1$ case. However, as $|M_1|$ tends to $|\mu|$ with $M_2 \gg |M_1|$, the negative eigenvalue (anti-symmetric) state eventually becomes the lightest one. In this region, its has substantially large bino-admixture compared to the positive eigenvalue state which pushes it down. This state flip happens in a larger region for negative $\mu$ compared to the positive $\mu$ case. In fig. 2.2(c) the sharp rise of $\delta m_1$ for large $M_2 \gtrsim 2$ TeV and $|M_1| \lesssim 1.5$ TeV appears as a consequence. Note that for negative $\mu$, the mixing in the chargino sector is rather small for similar $|\mu|$ and $M_2$ when compared to the positive $\mu$ case. Thus, $\tilde{\chi}_1^\pm$ can be the heaviest higgsino-like state in a substantial region of the parameter space for $M_2 \gtrsim 2$ TeV, as shown in fig. 2.2(d). Further, this state is never the lightest higgsino-like state, as happened for positive $\mu$.

We will further discuss the implications of the variation of $\Delta m_i$ among these light higgsino-like states with rather heavy gaugino mass parameters in section 3.

2.3 The spectrum

As we have already emphasized, the focus of this work is on higgsino-like NLSPs in a scenario with a right-sneutrino LSP. The choice of small $|\mu|$ is motivated by the “naturalness” criteria [6, 8, 9]. Thus we will mostly restrict our discussions to scenarios where the higgsino mass parameter $|\mu| \lesssim 500$ GeV. The gaugino mass parameters have been assumed to be heavy for simplicity; thus the light higgsino-like states are quite compressed in mass (fig. 2.2).
Figure 2.3. Schematic description of the mass spectrum with $|M_1|, M_2 \gg |\mu|$, and $m_{\tilde{\nu}_1} < |\mu|$. Here $|m_{\tilde{\chi}_2^0}| - |m_{\tilde{\chi}_1^\pm}| = \Delta m_2$, $|m_{\tilde{\chi}_1^0}| - m_{\tilde{\chi}_1^\pm} = \Delta m_1$.

Note that since the gaugino mass parameters are much heavier, the gaugino fraction in the higgsino-like states are small ($\mathcal{O}(10^{-2})$). However, $M_1$ and $M_2$ play significant role in determining $\Delta m_1$ and $\Delta m_2$ and also the hierarchy between the higgsino-like states. While for most parameter space the spectra shown in the left panel of fig. 2.3 is realized, for $M_1 < 0$ (i.e. sign($M_1 M_2$) = -1), it is possible to achieve the chargino as the lightest higgsino-like state which leads to a spectra as shown in the right panel of fig. 2.3. Further, with $\mu, M_1 < 0$ one can also have the chargino as the heaviest of the three higgsino-like state. However, as we will discuss subsequently in section 4, this does not contribute to any new signature, and we will therefore mostly focus on the spectra shown in the figure. Figure 2.3 schematically shows the mass hierarchies of our interest.

We consider the LSP to be dominantly right-sneutrino with a small left admixture ($\lesssim \mathcal{O}(10^{-3})$) which favors prompt decays of the charginos. While $\tilde{\chi}_1^0$ appears as the lightest higgsino-like state, the decay modes available to the chargino are $\tilde{\chi}_1^\pm \rightarrow l \tilde{\nu}_j^c$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^{\pm*}$, where $j, k$ corresponds to a particular lighter sneutrino species. The partial width to the 3-body decay mode, mostly coming from the off-shell $W$ boson mediated process, is suppressed by the small mass difference while small $y_{\nu}(\lesssim 10^{-6})$ suppresses the 2-body decay mode. In this scenario, the gaugino fraction in $\tilde{\chi}_1^\pm$, can contribute to the 2-body mode significantly in the presence of small left-right mixing ($\lesssim \mathcal{O}(10^{-3})$) in the sneutrino sector, thus giving a small fraction of left-sneutrino in the dominantly right-sneutrino LSP. It would be especially interesting to study the scenario where the 2-body decay mode into $l \tilde{\nu}$ starts to compete with the 3-body decay mode. Note that, $\Delta m_1 \gtrsim 1 \text{ GeV}$ ensures prompt decay of $\tilde{\chi}_1^\pm$ in the 3-body mode. For a particular $\Delta m_1$, and a fixed gaugino fraction in $\tilde{\chi}_1^\pm$ (for a fixed $\mu$, both vary with $M_1, M_2$, and tan $\beta$), this criteria decides the range of left-right mixing in the lighter sneutrinos, and thus the tri-linear soft-supersymmetry breaking parameter $T_{\nu}$. We illustrate this by quantifying the left-admixture required...
Figure 2.4. Variation of the partial decay width of $\tilde{\chi}_1^\pm \rightarrow l\tilde{\nu}$ versus $\sin(\theta^l)$ in logarithmic scale for $M_1 = -1.5$ TeV, $M_2 = 1.8$ TeV and gaugino fraction $\sim \mathcal{O}(10^{-2})$. Other parameters are same as discussed in Table 2. The colored palette corresponds to $T_\nu$, the soft left-right mixing parameter in the sneutrino sector. The plot shows the required $T_\nu$ and mixing angle $\sin(\theta^l)$ for prompt decay of the chargino. We focus on the values of $T_\nu$ in our study ensuring prompt decays of the chargino.

in fig. 2.4. As shown in fig. 2.4 we note that while for small $T_\nu$ and therefore for small left-right mixing in the sneutrino sector, $y_\nu$ dominates the decay process. As $T_\nu$ increases past $\mathcal{O}(10^{-2})$, the gaugino fraction plays a crucial role, which explains the rise of the partial width. Note that we have fixed the left-slepton mass at about 600 GeV. With $y_\nu \sim 10^{-6}$ prompt decay of the lightest chargino to the sneutrino and lepton is always ensured. However, for $y_\nu \sim 10^{-7}$ prompt decay of the chargino in the leptonic channel is not viable in the absence of left admixture. As seen in fig. 2.4, in this case $T_\nu \gtrsim \mathcal{O}(10^{-2})$ is required to ensure prompt decay in the leptonic channel. For smaller values of $T_\nu$, $y_\nu$ driven decay dominates. With the increase of $T_\nu$ (and therefore the left-sneutrino fraction in the lightest sneutrinos(s)), the gaugino fraction in $\chi_1^\pm$ dominates the decay process. The dip appears as a consequence of possible cancellation between the gaugino and the higgsino contributions to the vertex factor (e.g. $\propto (g_2 V_{11} \sin \theta^l - y_\nu V_{12} \cos \theta^l)$, $g_2$ is the SU(2) gauge coupling). Note that the mass splitting $\Delta m_1$ would also determine whether the chargino decays promptly or becomes long-lived if $y_\nu$ becomes too small. Note that, the particular choice of gaugino mass parameters correspond to $\Delta m_1 \lesssim 1$ GeV, and the partial width in the corresponding hadronic channel is quite small ($\simeq 10^{-16}$ GeV). Thus, the leptonic partial width resembles the total width of $\tilde{\chi}_1^\pm$. 
3 Survey of the relevant parameter space

We now consider the model parameter space, as described in the previous section, in the light of various constraints. The allowed decay channels of the light higgsino-like states and the corresponding branching ratios will be discussed in more detail later. Needless to emphasize that these would play an important role in deciding about the possible signatures at LHC.

3.1 General constraints

We implement the following general constraints on the parameter-space:

- The lightest CP-even Higgs mass $m_h$ has been constrained within the range :
  \[122 \leq m_h \text{ (GeV)} \leq 128\] [101–103]. While the experimental uncertainty is only about 0.25 GeV, the present range of ±3 GeV is dominated by uncertainty in the theoretical estimation of the Higgs mass, see e.g. [104] and references there.\(^3\)

- The lightest chargino satisfies the LEP lower bound: $m_{\tilde{\chi}^{\pm}} \geq 103.5$ GeV [105]. The LHC bounds, which depend on the decay channels of the chargino, will be considered only for prompt channels in more detail in section 4.

- The light sneutrino(s) (with small left-sneutrino admixture) can contribute to the non-standard decay channels of (invisible) Higgs and /or Z boson. The latter requires the presence of both CP-even and CP-odd sneutrinos below $\simeq 45$ GeV. Constraints from the invisible Higgs decay ($\simeq 20\%$) [106] and the Z boson invisible width ($\simeq 2$ MeV) [107] can impose significant constraints on the parameter space where these are kinematically allowed.

- We further impose $B_s \rightarrow \mu^+\mu^-$ [108] and $b \rightarrow s\gamma$ constraints [109].

3.1.1 Implication for neutrino mass

Recent analyses by PLANCK [110] imposes the following constraint on the neutrino masses :

\[\sum m_{\nu} \lesssim 0.7 \text{ eV}.\]

\(^3\)Note that, besides the MSSM contributions, rather large $T_\nu$ can induce additional contributions to the Higgs mass [63]. Our numerical estimation takes this effect into account.
In the present scenario, the neutrinos can get a tree-level mass, as is usual in the Type-I see-saw scenario. For \( y_\nu \sim 10^{-6} \), and \( M_R \sim 100 \text{ GeV} \), the active neutrino mass is of \( \mathcal{O}(0.1) \text{ eV} \). Further, as discussed in section 2.1, a non-zero Majorana mass term \( M_R \), and the corresponding soft-supersymmetry breaking term \( B_M \) introduce a splitting between the CP-even and CP-odd mass eigenstates of right-sneutrinos. In the presence of sizable left-right mixing, significant contribution to the Majorana neutrino mass can be generated at one-loop level in such a scenario, the details depend on the gaugino mass parameters [82, 89]. Thus, regions of large \( B_M \), in the presence of large left-right mixing in the sneutrino sector (induced by a large \( T_\nu \)) can be significantly constrained from the above mentioned bound on (active) neutrino mass. In fig. 3.1 we show the allowed region in the \( T_\nu - B_M \) plane. We consider \( y_\nu \in \{10^{-6}, 10^{-7}\} \) while the other parameters are fixed as follows: \( \mu = 300 \text{ GeV} \), \( M_3 = 2 \text{ TeV} \), \( M_{Q_3} = 1.5 \text{ TeV} \), \( T_t = 2.9 \text{ TeV} \), \( M_{L_{1/2}} = 600 \text{ GeV} \), \( m_{\nu}^{\text{soft}} = 100 \text{ GeV} \) and \( M_A = 2.5 \text{ TeV} \). While in the former case the tree-level and radiative contributions to the neutrino mass can be comparable (with each being \( \mathcal{O}(0.1) \text{ eV} \)), the radiative corrections often dominate for the latter. As shown in the figure, clearly larger \( T_\nu \) values are consistent with neutrino mass for smaller \( B_M \).
3.1.2 Implications for Dark Matter

![Graph](image)

**Figure 3.2.** In the left panel, the dependence of the relic abundance of $\tilde{\nu}_1$ has been shown on its mass and left-fraction. The right panel shows the allowed region respecting the direct detection constraint from XENON-1T.

Within the paradigm of standard model of cosmology the relic abundance is constrained as $0.092 \leq \Omega h^2 \leq 0.12$ [110]. Stringent constraints from direct search constraints require the DM-nucleon (neutron) interaction to be less than about $10^{-9}$ pb, which varies with the mass of DM, see e.g. LUX [111], PANDA-II [112] and Xenon-1T [113].

In figure 3.2, with $y_\nu \in \{10^{-6}, 10^{-7}\}$, $\tan \beta \in \{5, 10\}$, $\mu = -450$ GeV, $m_A = 600$ GeV and all other relevant parameters are fixed as before, we scan over the set of parameters $\{T_\nu, m_\tilde{\nu}, B_M\}$ (first generation only). We plot the left-admixture ($\sin \theta$) in the LSP required to obtain the thermal relic abundance and direct detection cross section against its mass in the left and the right panel respectively. We have used micrOMEGAs-3.5.5 [114] to compute the thermal relic abundance and direct detection cross-sections. For a right-sneutrino LSP, with a small left-admixture (say $\sin \theta \sim \epsilon$), the important annihilation processes are the following (keeping interactions up to $\sim \mathcal{O}(\epsilon^2)$):

- There are s-channel annihilation processes which are mediated by Higgs bosons. The vertex factor $\propto \epsilon(y_\nu M_R \pm T_\nu)$ (where the relative sign depends on the CP properties of the sneutrino LSP) comes from the F-term contribution to the scalar potential, as well as from the soft-supersymmetry breaking term. There is also a contribution from the D-term, with a vertex factor $\propto g^2 \epsilon^2 v$. Further a four-point interaction with the Higgs bosons originate from the D-term contribution with a vertex factor $\propto g^2 \epsilon^2$. These D-term contributions can become significant for larger $\epsilon$ i.e. for large $T_\nu \gtrsim \mathcal{O}(10^{-2})$. The dominant annihilation channels include $hh$, $W^\pm W^\mp$, $ZZ$, $t\bar{t}$. 

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• There are four-point gauge vertices $\propto g^2 \epsilon^2$ into $Z$-bosons that can contribute to the annihilation of sneutrinos. Further, thanks to vertices involving involving a CP-even and a CP-odd sneutrino and $Z$ boson ($\propto g \epsilon^2$), $\tilde{\nu}$ mediated $t/u$ channel process of similar strength can contribute to annihilation into $ZZ$ final state. Also $Z$-mediated $s$-channel processes involving a CP-even and a CP-odd sneutrino can contribute to the co-annihilation.

With $T_\nu \gtrsim O(10^{-3})$ being our choice of interest to allow left-right mixing in the sneutrino sector, the right-sneutrino LSP thermalizes with the (MS)SM particles via its interaction with left-sneutrino and Higgs bosons. In fact the most important annihilation channels involve left-right mixing in the sneutrino sector. However note that such an admixture also induces significant direct detection cross-section via $Z$ boson exchange. A small mass splitting of $O(100)$ keV between the CP-even and the CP-odd sneutrino can prevent the tree-level $Z$ boson-exchange cross-section kinematically at the tree-level [55, 115, 116]. In figure 3.2 we have chosen a mass difference of at least 1 MeV between the CP-even and the CP-odd states.\footnote{We have checked that with 1 MeV mass splitting and a left-admixture of $O(10^{-2})$, as is relevant for thermal relic, the heavier of the CP-even and the CP-odd state has a decay width of $\sim 10^{-20}$ GeV, mostly into the LSP and soft leptons/quarks via off-shell $Z$ boson. This corresponds to a lifetime of $\lesssim 10^{-3}$ s. Thus it would decay well before the onset of Big Bang Nucleosynthesis (BBN) and is consistent with constraints from the same.} While this ensures the absence of any $Z$ mediated contributions, there still exist t-channel contributions to the direct detection mediated by Higgs bosons. This contribution mostly comes from D-term, as well as the tri-linear term $T_\nu$, and is therefore proportional to the left-right mixing ($\epsilon$) in the sneutrino sector. As shown in the left panel of fig. 3.2, $\sin \theta$ of $O(0.1)$ is required to achieve the right thermal relic abundance while at the Higgs resonances ($m_A \sim 600$ GeV) a lower admixture can be adequate. With small enough $B_M$, such a sizable mixing can still be consistent with the observed neutrino mass. We have allowed for up to $O(10\%)$ tuning among the the relevant parameters (e.g. between the gaugino mass parameters), so that the radiative corrections do not lead to large neutrino mass [89, 117]. Further co-annihilation with the low-lying higgsino-like states ($|\mu| \sim 450$ GeV), when the LSP mass is close to 450 GeV, can also be effective. As shown in the right panel of the same figure, for $m_{DM} \lesssim 450$ GeV, most parameter space giving rise to the right thermal relic abundance is tightly constrained from direct searches. This is because while thermal relic abundance requires the left-right mixing $\epsilon$ in the sneutrino LSP to be $O(10^{-1})$, scattering cross-section with nucleons mediated by Higgs bosons prefer a lower admixture. In a nutshell, Xenon-1T result constrains the parameter region consistent with thermal relic abundance, the exceptions being the resonant annihilation and co-annihilation regions.

Note that for very small $T_\nu$ and $y_\nu \lesssim 10^{-6}$, the effective interaction strength of right-sneutrinos may be smaller than the Hubble parameter at $T \simeq m_{DM}$. In such a
scenario, non-thermal production, especially from the decay of a thermal NLSP, can possibly generate the relic abundance \cite{56–59}. Further, non-thermal productions can also be important in certain non-standard cosmological scenarios, e.g. early matter domination or low reheat temperature, see e.g. \cite{118, 119}. In addition, large thermal relic abundance can be diluted if substantial entropy production takes place after the freeze-out of the DM. In the subsequent sections, while focusing mainly on various collider signatures, we will not demand the thermal relic abundance to be satisfied by the benchmark scenarios.

3.2 Compressed Higgsino sector and their Decay properties

As our work is primarily motivated to study the collider implications of electroweakinos which are dominantly higgsino-like, their production and subsequent decay properties would have serious implications on search strategies at accelerator machines like LHC for these states. Note that the LHC searches would play an important role in constraining the higgsino mass parameter $\mu$ in the natural SUSY framework. We have already pointed out how the right L-R admixture in the sneutrino sector was helpful in ensuring a prompt decay for the light higgsino-like chargino, we now discuss the other relevant decay channels in detail.

Since we have assumed a compressed higgsino spectrum, together with a mostly right-sneutrino LSP, the light higgsino states include $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ and at least one generation of CP-odd and/or CP-even sneutrino LSP as described in section 2. In fig. 2.2 we showed that for a fixed $|\mu|$, the hierarchy and the mass differences between the higgsino-like states are affected significantly by the choice of the gaugino mass parameters $M_1$, $M_2$, and $\text{sign}(\mu)$. In a similar compressed scenario within the MSSM, the higgsinos $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ decay into soft leptons or jets \cite{120} and $\tilde{\chi}_1^0$, producing $E_T$. These mostly receive contributions from the $Z$ and $W$ boson mediated processes respectively. Scenarios with compressed higgsinos have been studied in the light of recent LHC data \cite{22–27}. For smaller mass differences, $130 \text{ MeV} \lesssim \Delta m_1 \lesssim 2 \text{ GeV}$, the effective two-body process $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ \cite{121–123} can dominate the hadronic branching fraction. Further, when $\tilde{\chi}_2^0$ is also almost degenerate with $\tilde{\chi}_1^\pm$, for an even smaller mass difference $\Delta m_2$, $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ can become significant \cite{124–127}. Note that while the three-body decay mode ($\pi^\pm \tilde{\chi}_1^0$) suffers from phase space suppression ($((\Delta m)^5)$, the two-body mode ($\gamma \tilde{\chi}_1^0$) is also suppressed by a loop factor.

In addition to the above decay channels of the compressed higgsino-like states, the present scenario with a sneutrino LSP offers additional decay channels to the lighter sneutrinos. While a neutralino decaying into a sneutrino LSP and a neutrino would lead to missing transverse energy (as in the case for MSSM) without altering the signal topology if the neutralino was the LSP, a chargino decaying into a sneutrino and a lepton would have significant impact on the search strategies. For a pure right-sneutrino LSP this decay is driven by $y_\nu$. In the presence of large $T_\nu$ and therefore a large left-right mixing in the sneutrino LSP, a gaugino fraction of $\gtrsim O(10^{-2})$ in
Table 3.1. Relevant input parameters for the parameter-space scan have been presented. Other parameters kept at fixed values include: $M_R = 100$ GeV, $B_M = 10^{-3}$ GeV$^2$, $M_3 = 2$ TeV, $M_{Q_3} = 1.3$ TeV, $T_t = 2.9$ TeV, $M_{L_{1/2}} = 600$ GeV, $m_{\tilde{\nu}}^{soft} = 100$ GeV, $M_A = 2.5$ TeV, and $y_\nu = 10^{-7}$.

The higgsino-like chargino begins to play a prominent role as the decay is driven by a coupling proportional to $g_\delta \epsilon$ where $\delta$ represents the gaugino admixture and $\epsilon$ represents the L-R mixing in the sneutrino sector. The presence of multiple flavors of degenerate sneutrinos would lead to similar decay probabilities into each flavor and would invariably increase the branching to the two-body leptonic mode when taken together.

In the present context, as has been emphasized, only prompt decays into the leptonic channels such as $\tilde{\chi}_1^\pm \to l \tilde{\nu}_i$ and $\tilde{\chi}_i^0 \to \tilde{\chi}_1^\pm j_s j'_s$, where $j_s, j'_s$ denote soft-jets or soft-leptons can give us a signal with one or more hard charged leptons in the final state. Since the latter consists of $\tilde{\chi}_1^\pm$ in the cascade, it can also lead to leptonic final states. These branching fractions would be affected by any other available decay channels and therefore it is important to study the different regions of parameter space for all possible decay modes of the light electroweakinos. As shown in fig. 2.2, while in most of the parameter space $\tilde{\chi}_1^0$ is the lightest higgsino-like state, and $\tilde{\chi}_1^\pm$ is placed in between the two neutralinos (i.e. $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^0}$), it is also possible to have $\tilde{\chi}_1^\pm$ as the lightest or the heaviest higgsino-like state. The important competing modes for $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ where $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^0}$ include (a) $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 j_s j'_s/\pi^\pm$, (b) $\tilde{\chi}_2^0 \to \tilde{\chi}_1^\pm j_s j'_s/\gamma$ and (c) $\tilde{\chi}_2^0 \to \tilde{\chi}_1^+ j_s j'_s/\pi^\mp$ where (c) is usually small. However, if $\tilde{\chi}_1^\pm$ is the lightest higgsino-like state, decay modes (b) and (c), together with $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^\pm j_s j'_s/\pi^\mp$ can be present. Similarly, when $\tilde{\chi}_1^\pm$ is the heaviest higgsino-like state, decay modes (a), (b) and $\tilde{\chi}_1^\pm \to \tilde{\chi}_2^0 j_s j'_s/\pi^\pm$ can be present, although the latter would be sub-dominant.

In figures 3.3 and 3.4 we show the variation of branching fraction in the leptonic decay channels $\tilde{\chi}_1^\pm \to l \tilde{\nu}_i$ and $\tilde{\chi}_i^0 \to l^\pm \tilde{\nu}_i W^{\mp*}$. The relevant parameters for the scan can be found in table 3.1.
Figure 3.3. Variation of the leptonic branching ratios of $\tilde{\chi}_1^\pm \to l \tilde{\nu}$ and $\tilde{\chi}_2^0 \to l \tilde{\nu} W^*$ against the bino soft mass parameter, $M_1$ for the Higgsino mass parameter, $\mu = 300$ GeV. The wino soft mass parameter $M_2$ is shown in the palette.

Figure 3.4. Variation of the leptonic branching ratios of $\tilde{\chi}_1^\pm \to l \tilde{\nu}$ and $\tilde{\chi}_2^0 \to l \tilde{\nu} W^*$ against the bino soft mass parameter, $M_1$ for the Higgsino mass parameter, $\mu = -300$ GeV. The wino mass parameter $M_2$ is indicated in the palette.

Since we have not varied the parameters in the sneutrino sector, the sneutrino masses and mixing matrices do not change. Consequently the two body partial decay widths $\Gamma(\tilde{\chi}_1^\pm \to l \tilde{\nu}_i)$ and $\Gamma(\tilde{\chi}_2^0 \to \nu \tilde{\nu}_j)$ are only affected by the variation of the gaugino-admixture in the higgsino-like states. However, the heavy gaugino mass parameters do affect the mass splittings $\Delta m_1$ and $\Delta m_2$ through mixing and can even alter the hierarchy. These alterations in the spectrum mostly affect the 3-body decay modes described above which has a significant effect on the branching ratio.

As shown in fig. 2.2(a), for $\text{sgn}(\mu) = +$ (i.e. $\mu = 300$ GeV) and for negative $M_1$, $\Delta m_1$ is almost entirely $\lesssim 1$ GeV. Also, for large $M_2$ and $|M_1| \lesssim 2$ TeV, $\tilde{\chi}_1^\pm$ can be lightest higgsino-like state. Consequently, the three-body/pion decay mode
of the chargino ($\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 j_s j'_s / \pi^\pm$) is either absent or very small. Note that the three-body decay mode scales as $(\Delta m_1)^5$. Therefore, the leptonic branching fraction is very close to 1 as shown in fig. 3.3(a). However, for small $|M_1|$, and large $M_2$ this branching is somewhat reduced to about 0.8. This is because in this region $\Delta m_1$ increases to about 2 GeV allowing a larger three-body partial width. In addition a large $M_2$ also leads to a small gaugino fraction in $\tilde{\chi}^\pm_1$ thus reducing the two-body leptonic partial width. Note that in this region the negative eigenvalue state becomes $\tilde{\chi}^0_1$. In the positive $M_1$ region the branching ratio increases as $M_1$ increases. This can be attributed to the consistent decrease in $\Delta m_1$ (fig. 2.2(a)) and therefore of the three-body partial decay width.

Fig. 3.3(b) shows the variation of $\text{Br}(\tilde{\chi}^0_2 \to \tilde{\chi}^\pm_1 W^{\mp*})$ as a function of $M_1$ and $M_2$. For negative $M_1$, generally the branching grows for larger $\Delta m_2$ (fig. 2.2(b)) and decreases for smaller $M_2$ as the mass splitting goes down. Note that for most regions of the parameter space the negative eigenvalue (symmetric) state is $\tilde{\chi}^0_2$ and the nature of the state changes for large $M_2$ values as $|M_1|$ approaches $\mu$. In this region the three-body mode into $\tilde{\chi}^0_1$ is more phase-space suppressed compared to the decay mode into $\tilde{\chi}^\pm$. Further, as $|M_1|$ approaches $\mu$, the symmetric state, which mixes well with the bino, acquires larger bino fraction and there can be a cancellation in the vertex factor $\propto g_2 (N_{22} - \tan \theta_W N_{21})$ for the two-body decay width into sneutrino. This can reduce the corresponding width and then increase again as $|M_1|$ decreases. Thus the branching ratio for the three-body decay shows a discontinuous behavior in such regions. For positive $M_1$, the branching ratio shows similar pattern as $\Delta m_2$ variation, as expected. The negative eigenvalue (symmetric) state is $\tilde{\chi}^0_2$ in this case, which have smaller gaugino fraction compared to the anti-symmetric state. Larger $\Delta m_1$ in this region implies that the three-body decay into $\tilde{\chi}^0_1$ can be larger, and consequently $\text{Br}(\tilde{\chi}^0_2 \to \tilde{\chi}^\pm_1 j_s j'_s)$ is rather small.

The case for $\mu = -300$ GeV (negative $\mu$), has been shown in figure 3.4. In panel (a), the branching ratio of $\tilde{\chi}^\pm_1 \to \tilde{\nu}_j j$ is shown. The figure clearly shows that the branching ratio in this channel decreases as $M_2$ increases. Although, for large $M_2$, the gaugino fraction in $\tilde{\chi}^\pm_1$ would be small, thus possibly reducing the partial width in this two-body decay mode; smaller $\Delta m_1$ in this region ensures that the competing three-body mode decreases even more. Therefore, the branching ratio in the two body mode is enhanced. This holds true for almost the entire range of $M_1$. The
feature in the negative $M_1$ region, as $|M_1|$ approaches $|\mu|$, where the branching ratio rises faster for larger $M_2$ values, corresponds to a similar fall in $\Delta m_1$ (see fig. 2.2(c)). As has been explained in section 2, in this region as $|M_1|$ decreases and approaches $|\mu|$ the symmetric (anti-symmetric) state becomes $\tilde{\chi}^0_2$ ($\tilde{\chi}^0_1$).

In figure 3.4(b) the variation of $\text{Br}(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^\pm_1 j_s j_s')$ with $M_1, M_2$. For negative $M_1$, this branching ratio increases with decreasing $M_2$, since the corresponding mass difference $\Delta m_2$ also increases (see figure 2.2). The larger $M_2$ values are not shown for $M_1 < 0$, since $\tilde{\chi}^\pm_1$ becomes the heaviest higgsino-like state in this region. Thus, $\Delta m_2 < 0$ as shown in see fig. 2.2(d), and this decay mode does not contribute. For $M_1 > 0$ smaller $M_2$ values correspond to larger branching fractions, since $\Delta m_2$ becomes larger, increasing the partial width. However, for large $M_2$ values, the partial width decreases rapidly as $\Delta m_2$ decreases.

Note that $T_\nu = 0.5$ GeV has been used in the figure. For smaller values of $T_\nu$ the leptonic branching ratio of $\tilde{\chi}^\pm_1$ would generally be reduced when it is not the lightest higgsino-like state. However, the generic features described above would remain similar. Note that, $y_\nu \sim 10^{-6}$ can lead to prompt decay even in the absence of large left-admixture, as induced by large $T_\nu$. Therefore, even for small $T_\nu \lesssim O(10^{-2})$, for certain choice of the gaugino mass parameters, the leptonic branching can be competing, and thus would be relevant to probe such scenario at collider.

4 Signatures at LHC

We now focus on the LHC signal of the higgsino-like electroweakinos in the presence of a right sneutrino LSP. In section 3.2 we discussed the various decay modes available to $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ in presence of a sneutrino LSP. As pointed out, the decay properties not only depend on the mixing among the various sparticle components but also crucially on the mass splittings. The LHC signals would then reflect upon the above dependencies on the parameter space. We therefore look at all possible signals for different regions of $\Delta m_{1/2}$ and $T_\nu$. For regions of $\Delta m_{1/2}$ where the chargino decays non-promptly to pions, the chargino travels in the detector for some length and then decays into a soft pion and neutralino. Since both decay products are invisible, the relevant search channel at LHC is the disappearing tracks [26, 27, 128]. Since both the two body and three body decays may compete when the mass splitting $\Delta m_{1/2}$ and $T_\nu$ roles are evenly matched for the 3-body and 2-body decays respectively, alternate signals to leptonic channels worth looking at would be mono-jet signals [129] or photon(s) and/or associated with hard ISR jets and missing energy since the decay products from the three body decays are soft. Our focus on the paper is primarily on the prompt decay of the chargino to hard leptons (small $\Delta m_{1/2}$ and large $T_\nu$) which are clean signals to observe at LHC.
The following production channels are of interest to us:

\[ p \, p \to \tilde{\chi}_1^\mp \tilde{\chi}_1^0, \, \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \, \tilde{\chi}_1^0 \tilde{\chi}_2^0, \, \tilde{\chi}_1^\pm \tilde{\chi}_2^0, \, \tilde{l} \tilde{l}, \, \tilde{l} \tilde{\nu}, \, \tilde{\nu} \tilde{\nu} \tag{4.1} \]

where the sleptons and sneutrinos are heavier than the electroweakinos here. The LSP pair production is excluded in the above list.

\[ \begin{array}{c}
A = \tilde{\chi}_1^+ \tilde{\chi}_1^- \\
B = \tilde{\chi}_1^0 \tilde{\chi}_1^- \\
C = \tilde{\chi}_1^0 \tilde{\chi}_2^0 \\
D = \tilde{\chi}_1^0 \tilde{\chi}_1^0 \\
\end{array} \]

\[ \begin{array}{c}
\tilde{t}_1 \text{ and } \tilde{b}_1 \text{ are of mass } \sim 1.4 \text{ TeV.} \\
\end{array} \]

The processes as given in eq. 4.1 are in decreasing order of production cross-sections as obtained from Prospino [130–132]. The associated chargino neutralino pair, i.e \( \tilde{\chi}_1^\pm \tilde{\chi}_1^0 \) production has the largest cross-section followed by the chargino pair production, \( \tilde{\chi}_1^\pm \tilde{\chi}_1^- \). In the pure higgsino limit, the pair production cross-section of \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \) and \( \tilde{\chi}_2^0 \tilde{\chi}_2^0 \) are negligible compared to the other processes. Since the strong sector is kept decoupled and the compressed higgsino sector leads to soft jets and leptons, the only source of hard jets are from initial-state radiations (ISR). The suppressed jet multiplicity in the signal could prove to be a potent tool for suppressing SM leptonic backgrounds coming from the strongly produced \( t \bar{t} \) and single top subprocesses which would give multiple hard jets in the final state in association with the charged leptons. Therefore we shall focus on the following leptonic signals with low hadronic activity to probe such a compressed higgsino sector in presence of \( \tilde{\nu} \) LSP:

- Mono-lepton + \( \leq 1 \) jet + \( \not{E}_T \)
• Di-lepton + 0 jet + $E_T$

The mono-lepton signals would come from the pair production of $\tilde{\chi}^+_1 \tilde{\chi}_1^-$, ($\tilde{\chi}^+_1 \rightarrow l \tilde{\nu}$ and $\tilde{\chi}^+_i \rightarrow \tilde{\nu}^* W^{\pm}$), and associated pair production, $\tilde{\chi}^+_1 \tilde{\chi}^0_i$ with $i = 1, 2$ ($\tilde{\chi}^+_1 \rightarrow l \tilde{\nu}$ and $\tilde{\chi}^0_i \rightarrow \nu \tilde{\nu}$). A smaller contribution also comes from the production of $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ ($\tilde{\chi}^0_{2/1} \rightarrow \tilde{\chi}^+_1 W^{*+}$ and $\tilde{\chi}^0_{1/2} \rightarrow \tilde{\nu}^* \tilde{\nu}$) leading to missing energy. Among the di-lepton signals we look into both opposite sign leptons and same sign lepton signal with missing energy. Opposite sign leptons arise from the pair produced $\tilde{\chi}^+_1 \tilde{\chi}^-_1$, with the chargino decaying leptonically as $\tilde{\chi}^+_1 \rightarrow l \tilde{\nu}$. In regions of the parameter space where $\tilde{\chi}^0_{2/1}$ is heavier than $\tilde{\chi}^0_1$, $\tilde{\chi}^+_1 \tilde{\chi}^0_i$, $i = 1, 2$ process may contribute to the di-lepton state via $\tilde{\chi}^0_i \rightarrow \tilde{\chi}^+_1 W^{*+}$ followed by $\tilde{\chi}^+_1 \rightarrow l \tilde{\nu}$. In such cases, there could be either opposite sign di-lepton signal or same-sign di-lepton signal owing to the Majorana nature of the neutralinos ($\tilde{\chi}^0_i$). A similar contribution to both channels come from $\tilde{\chi}_1 \tilde{\chi}^0_2$ with $\tilde{\chi}^0_{1/2} \rightarrow \tilde{\chi}^+_1 W^{*+}$. There also exist sub-leading contributions from slepton pair productions which become only relevant for light sleptons in the spectrum.

It is worth pointing out that in very particular regions of the parameter space $\tilde{\chi}^+_1$ is the NLSP and therefore always decays to a hard lepton and sneutrino LSP. In such cases, signal rates for the di-lepton channel would be most interesting and dominant rates for same-sign di-lepton would be a particularly clean channel will be important to probe high values of $\mu$ very effectively. This is very particular of the parameter region when $M_1$ is negative and one has a sneutrino LSP (carrying lepton number).

4.1 Constraints on electroweakino sector from LHC

LHC has looked for direct production of lightest $\tilde{\chi}^+_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ in both run 1 and run 2 searches at 7, 8 and 13 TeV respectively and reinterpreted them assuming simplified models with and without intermediate left and right sleptons with $\tilde{\chi}^0_1$ LSP contributing to $E_T$ (see Table 4.1). Assuming 100% leptonic branching of the sparticles, CMS has ruled out degenerate wino-like $m_{\tilde{\chi}^+_{1/2}}$, $m_{\tilde{\chi}^0_2} > 1.2$ TeV for a bino-like $m_{\tilde{\chi}^0_2} < 600$ GeV from same-sign di-lepton, three lepton and four lepton searches with at most 1 jet [133]. For the nearly compressed higgsino sector assuming mass degeneracy of the lightest chargino ($\tilde{\chi}^+_1$) and next-to-lightest neutralino ($\tilde{\chi}^0_2$), the mass limits relax up to 300 GeV for $m_{\tilde{\chi}^0_1} \sim 280$ GeV from these searches. Among the alternate channels probed by LHC to explore the compressed higgsino sector are soft opposite sign di-leptons searches with leptons having $p_T > 3.5$ GeV [134]. The mass limits on the compressed higgsino sector further relax to $\sim 230$ GeV for $m_{\tilde{\chi}^0_1} \sim 210$ GeV.

Other searches with low hadronic activity involve a recent search from ATLAS collaboration [135] which look for di-lepton and trilepton signal with no jets. The di-lepton search from chargino pair production, with charginos decaying to the neutralino LSP via intermediate sleptons sets a limit on the $m_{\tilde{\chi}^+_1} > 720$ GeV for $m_{\tilde{\chi}^0_1} <$
Final State & Luminosity (in fb$^{-1}$) & ATLAS & CMS \\
\hline
1 lepton + $E_T$ & 13.3, 36 & [136] & [137] \\
2 same-sign leptons + $E_T$ & 35.9 & - & [133] \\
2 leptons + $E_T$ & 36 & [135] & [138] \\
3 or more leptons + $E_T$ & 36,35.9 & [135] & [133], [139] \\
\hline
\caption{LHC searches at 13 TeV with few jets relevant for our study.}

200 GeV [135]. On the other hand, the trilepton channel excludes mass degenerate $m_{\tilde{\chi}_2^\pm} \sim 1.15$ TeV for $m_{\tilde{\chi}_1^0}$ up to 580 GeV [135]. A trilepton search from associated $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, decaying to the LSP via $W$ and $Z$ bosons respectively which then decay leptonically, leads to a bound close to 480 GeV on the mass degenerate chargino and next-to-lightest neutralino for LSP masses close to 100 GeV [135]. It is important to note, that limits from channels associated with multiple jets usually have higher SM background events leading to slightly weaker limits. For example in the ATLAS di-lepton search with jets reinterpreted from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ associated production, with the sparticles decaying via ($W \rightarrow jj$) and ($Z \rightarrow l^+l^-$) and the LSP, the limits on the mass degenerate $m_{\tilde{\chi}_2^0}$: $m_{\tilde{\chi}_2^\pm} \sim 580$ GeV for $m_{\tilde{\chi}_1^0} < 150$ GeV, being 140 GeV lighter than the limits from di-lepton + 0 jet searches. We reinterpret and take into account these limits in the context of our study and impose any constraints that apply on our parameter space.

4.2 Benchmarks

In the context of natural supersymmetry with degenerate first and second generation sneutrino as LSP, we look into regions of parameter space allowed by neutrino physics constraints, LHC data and direct detection cross-section constraints. We select four representative points of the parameter space and analyze their signal at the current run of LHC. We check the viability of the chosen benchmarks for multi-leptonic signatures by testing the signal strengths against existing experimental searches implemented in the public software CheckMATE [140, 141]. Amongst the searches implemented in CheckMATE, mono-jet along with missing energy search [142] provides the most stringent constraint. Among the other 13 TeV searches as listed in Table 4.1, same-sign di-lepton and opposite-sign di-lepton searches also impose a stringent constraint on the current scenario. The allowed same-sign di-lepton branching is restricted to 4% or lower for $\mu = 300$ GeV. A higher value of $\mu$ and hence a lower production cross-section allows a larger same-sign di-lepton branching thereby allowing us to probe a wider range of the parameter space.

We choose parameters with $|\mu| = 300$ GeV as listed in Table 4.2. The choice of the benchmarks ensure prompt decay of the chargino to a hard lepton and LSP, i.e, $\Gamma > 10^{-13}$ GeV. The gaugino mass parameters $M_1$ and $M_2$ are large such that the spectrum consists of two light higgsino-like neutralinos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and a nearly degener-
ate light higgsino-like $\tilde{\chi}_1^\pm$ within $\mathcal{O}(2-4)$ GeV. However there is considerable amount of freedom in choosing the relative sign among the soft parameters $M_1$ and $M_2$ and $\mu$. Both the first and second generation squarks as well as gluino soft mass parameter are set to $\sim 2$ TeV. The stops are also kept heavy to ensure the light CP-even Higgs mass and signal strengths to be within the allowed experimental values. Both the first two generation left and right sleptons are kept above the higgsino sector and when possible within the reach of LHC, in the range 360–600 GeV, in the different benchmark points studied. Following our discussion in section 2.2 on the $M_1 - M_2$ dependence of the masses, the benchmarks represent points in the following regions of parameter space:

- **Region A**: $M_1 > 0$, $M_2 > 0$ and $\mu > 0$, with $\tilde{\chi}_1^0$ as NLSP (BP1).
- **Region B**: $M_1 > 0$, $M_2 > 0$ and $\mu < 0$, with $\tilde{\chi}_1^0$ as NLSP (BP2-a and BP2-b).
- **Region C**: $M_1 < 0$, $M_2 > 0$ and $\mu > 0$, with $\tilde{\chi}_1^\pm$ as NLSP (BP3).

BP1 represents a point in the $M_1 M_2 > 0$ and $\mu > 0$ plane with $M_1 = 1.5$ TeV, $M_2 = 1.8$ TeV, $\tan \beta = 5$ and $\Delta m_{1/2} \sim 2$ GeV. The LSP mass is $\sim 140$ GeV and therefore there is a large mass gap between the higgsinos and the LSP, $\Delta M(= m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}_{LSP}}) \sim 162$ GeV. The first two generation sleptons are of masses $\sim 360$ GeV to facilitate left-right mixing in the sneutrino sector. The mixing in the left-right sneutrino is $\mathcal{O}(10^{-4})$, such that for BP1 the three body decay of $\tilde{\chi}_1^\pm$, i.e. BR($\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^{\pm*}$) dominates ($\sim 88\%$) over the two-body decay, BR($\tilde{\chi}_1^\pm \rightarrow l \tilde{\nu}$) ($\sim 12\%$). For a heavier slepton mass, a larger $T_\nu$ value is required for a similar left-right mixing angle and vice versa. Thus, we can fix the leptonic branching of the chargino either by lowering the left slepton mass or increasing $T_\nu$, and hence the left-right mixing in the sneutrino sector. Since the softer decay products from the three body decay produced from the off-shell $W$ pass undetected owing to the compression in the electroweakino sector, the two body leptonic decay is of interest, although subdominant. $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ dominantly decay to a $\nu \tilde{\nu}$ pair contributing to missing energy signal. The dominant signals to look for in this case are mono-lepton + $E_T$ and to a lesser extent opposite-sign and same-sign di-lepton events owing to the small leptonic branching of chargino.

Further, we choose a benchmark BP2-a which is similar to BP1, but has an increased left-right mixing in the sneutrino sector and hence a larger leptonic branching of the chargino. It represents a point in the $M_1 M_2 > 0$ and $\mu < 0$ plane with $M_1 = 2.4$ TeV and $M_2 = 1$ TeV. Note that for $\mu < 0$ a larger region of parameter space exists. Here $\Delta m_4 = 4$ GeV and $\Delta m_5 = 4$ GeV such that BR($\tilde{\chi}_1^\pm \rightarrow l \tilde{\nu}$) $\sim 37\%$ and BR($\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm W^{\pm*}$) $\sim 9\%$. We focus only on signals from the electroweakino sector and choose to keep the first and second generation left and right sleptons
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Parameters & BP1 & BP2–a & BP2–b & BP3 \\
\hline
$\mu$ & 300 & -300 & -300 & 300 \\
$\tan \beta$ & 5 & 10 & 10 & 5 \\
$M_1$ & 1500 & 2400 & 2000 & -860 \\
$M_2$ & 1800 & 1000 & 1000 & 2500 \\
$M_3$ & 2000 & 2000 & 2000 & 2000 \\
$M_A$ & 2500 & 2500 & 2500 & 2500 \\
$T_t$ & 2900 & -2500 & -2500 & 2900 \\
$M_R$ & 100 & 100 & 100 & 100 \\
$BM_R$ (GeV$^2$) & $10^{-3}$ & 143 & 143 & $10^{-3}$ \\
$m_{\tilde{\nu}}$ & 100 & 131 & 245 & 245 \\
$Y_{\nu}$ ($\times 10^{-7}$) & 1 & 1 & 1 & 1 \\
$T_{\nu}$ & 0.02 & 0.36 & 0.8 & 4.0 \\
\hline
$m_{\tilde{\chi}^\pm_1}$ & 303.6 & 307.6 & 307.5 & 305.4 \\
$m_{\tilde{\chi}^0_1}$ & 301.7 & 303.6 & 303.6 & 305.5 \\
$m_{\tilde{\chi}^0_2}$ & 305.8 & 311.6 & 311.5 & 305.8 \\
$m_{\tilde{\ell}_1}$ & 1034.6 & 1039.3 & 1024.7 & 1514.8 \\
$m_{\tilde{b}_1}$ & 1064.3 & 1063.2 & 1057.8 & 1552.1 \\
$m_{\tilde{\ell}_L}$ & 380.3 & 617.1 & 617.5 & 617.9 \\
$m_{\tilde{\ell}_R}$ & 364.5 & 601.5 & 606.7 & 608.5 \\
$m_{\tilde{\nu}_L}$ & 372.4 & 611.7 & 611.7 & 612.9 \\
$m_{\tilde{\nu}_R}$ & 141.4 & 163.9 & 264.1 & 264.6 \\
$m_h$ & 124.6 & 126.1 & 126.1 & 124.3 \\
$\Delta m_{CP}$ (MeV) & 0.004 & 900 & 900 & 0.004 \\
$\Delta m_1$ & 1.9 & 4.0 & 4.0 & -0.1 \\
$\Delta m_2$ & 2.2 & 4.0 & 4.0 & 0.5 \\
$\Delta M$ & 162.2 & 143.4 & 43 & 40.9 \\
$\sin \theta^j (\times 10^{-3})$ & 0.02 & 0.18 & 0.46 & 2.24 \\
$BR(\tilde{\chi}^+_1 \rightarrow l \tilde{\nu})$ & 0.13 & 0.37 & 0.34 & 1.0 \\
$BR(\tilde{\chi}^0_2 \rightarrow W^{\mp*} \tilde{\chi}^\pm_1)$ & 0.12 & 0.09 & 0.09 & 0.0001 \\
$BR(\tilde{\chi}^0_2 \rightarrow W^{\mp*} \tilde{\nu}W^{\mp*})$ & 0.015 & 0.033 & 0.031 & 0.0001 \\
\hline
\end{tabular}
\caption{Low energy input parameters and sparticle masses for the benchmarks used in the current study. All soft mass parameters and mass differences are in GeV units. Mass differences amongst the different higgsino sector sparticles, $\Delta m_1$ and $\Delta m_2$, are as defined in Section 2.2. Additionally, $\Delta M = m_{\tilde{\chi}^+_1} - m_{\tilde{\nu}}$ represents the mass gap between the chargino and the sneutrino LSP and $\theta^j$ represents the mixing angle between the lightest left and right sneutrinos.}
\end{table}

$\sim 600$ GeV such that their production cross-sections are negligible at 13 TeV LHC, thus reducing any additional contributions to the leptonic final states.

We choose another spectrum BP2–b similar to BP2–a but with a heavier LSP
mass. The former represents a lighter LSP, \( m_{\tilde{\nu}_{\text{LSP}}} \sim 164 \text{ GeV} \) and with \( \Delta M \sim 140 \text{ GeV} \) whereas the latter represents a heavier LSP scenario with \( m_{\tilde{\nu}_{\text{LSP}}} \sim 264 \text{ GeV} \) such that \( \Delta M \sim 40 \text{ GeV} \). Thus, we choose a nearly compressed spectrum BP2-b where the leptons are much softer as compared to those of BP2-a in order to study effectively the prospects of such a spectrum in presence of a \( \tilde{\nu} \) LSP. The dominant signals to look for BP2-a and BP2-b are mono-lepton, opposite-sign di-lepton and same-sign di-lepton along with missing transverse energy.

BP3 represents a spectrum with \( M_1 M_2 < 0, \mu > 0 \) with \( M_1 = -860 \text{ GeV}, M_2 = 2.5 \text{ TeV} \) and \( \tan \beta = 5 \). We also choose a large left-right sneutrino mixing (\( O(10^{-3}) \)) while the LSP mass is 264 GeV. This leads to a tightly compressed electroweakino sector with \( \tilde{\chi}_1^\pm \) as the NLSP as discussed in section 2.2. Hence the only allowed decay of the chargino is the two body leptonic decay to the LSP with \( \text{BR} (\tilde{\chi}_1^\pm \rightarrow l \tilde{\nu}) = 100\% \). Thus this region of parameter space favors the di-lepton channel with missing energy from chargino pair production. However the di-lepton channel suffers from a huge SM background and is much difficult to observe. Again the larger cross section for chargino-neutralino production only contributes to the mono-lepton channel as the decay of the heavier neutralinos to the chargino is rather suppressed for this benchmark in order to respect the bounds from existing same-sign di-lepton searches. Hence for this particular benchmark the dominant signal to look for is mono-lepton + \( E_T \) and to a lesser extent via the opposite sign di-lepton + \( E_T \). However, other choices of benchmark points in this region of parameter space would allow same-sign di-lepton signal along with missing energy making it very interesting and clean mode for discovery. This can be the preferred channel but for much larger \( \mu \).

4.3 Collider Analyses

Simulation set-up and Analyses

Our focus in this study is on leptonic channels with up to one ISR jet (\( p_T > 40 \text{ GeV} \)). We consider no extra partons at the matrix element level while generating the parton-level events for the signal using MadGraph-v5 [143–145]. Following the event generation at parton-level, showering and hadronisation of the events are performed using Pythia-v8[146]. Subsequently detector simulation is performed using Delphes-v3 [147–149]. Default dynamic factorization and renormalization scales of MadGraph-v5 have been used with CTEQ6L [150] as the parton distribution functions (PDF). Jets are reconstructed using Fastjet [151] with a minimum \( p_T \) of 20 GeV in a cone of \( \Delta R = 0.4 \) using the anti-\( k_t \) algorithm [152]. The charged leptons (\( e, \mu \)) are reconstructed in a cone of \( \Delta R = 0.2 \) with the maximum amount of energy deposit allowed in the cone limited to 10\% of the \( p_T \) of the lepton. Photons are also reconstructed similar to the leptons in a cone of \( \Delta R = 0.2 \), with the maximum energy deposit in the cone being at most 10\% of the \( p_T \) of the photon. All the benchmarks are checked against the public software CheckMATE [140, 141] to see if they pass 8
TeV and existing 13 TeV limits at LHC. SM backgrounds have also been generated using MadGraph-v5, Pythia-v6 [145] and visible objects reconstructed at the detector level using Delphes-v3 [147–149]. Signal and background analysis has been performed using MadAnalysis-v5 [153–155].

**Primary Selection Criteria**

We choose the following basic criteria for leptons (only $e^\pm$ and $\mu^\pm$), jets and photons for both signal and background:

- We select leptons ($e$, $\mu$) satisfying $p_T > 10$ GeV and $|\eta| < 2.5$.
- We choose photons with $p_T > 10$ GeV and $|\eta| < 2.5$.
- Reconstructed jets are identified as signal jets if they have $p_T > 40$ GeV and $|\eta| < 2.5$.
- Reconstructed b-tagged jets are identified with $p_T > 40$ GeV and $|\eta| < 2.5$.
- Jets and leptons are isolated such that $\Delta R_{lj} > 0.4$ and $\Delta R_{ll} > 0.2$.

![Figure 4.2](image-url)

**Figure 4.2.** Normalized distributions for lepton and jet multiplicity for benchmark **BP2** and dominant SM backgrounds channels, respectively.

### 4.4 Mono-lepton + ≤ 1 jet + $E_T$ signal

Presence of a sneutrino LSP opens up decay channels of the lightest chargino and neutralino to a lepton/neutrino and sneutrino respectively via the left-right mixing in the sneutrino sector. In such cases, mono-lepton signals with missing energy and few jets (mainly from ISR) arise dominantly from $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with $\tilde{\chi}_1^\pm \rightarrow l \tilde{\nu}$ and
\tilde{\chi}^0_{1/2} \rightarrow \nu \tilde{\nu}. \) Sub-dominant contributions to the signal may also arise from \( \tilde{\chi}^\pm_1 \tilde{\chi}^\pm_1 \) pair production when one of the chargino decays to a soft lepton (via the three body decay to the neutralino) and the other one decays to a hard lepton and the LSP. Smaller contributions to the signal also come from \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) production with \( \tilde{\chi}^0_2 \) decaying to a chargino and soft decay products while \( \tilde{\chi}^0_1 \) decays invisibly or vice versa if the chargino is the lightest among the higgsinos.

Dominant background to this signal come from SM processes:

- \( l\nu + 0,1 \) jets (including contributions from both on-shell and off-shell W boson),
- \( t\bar{t} \) (where one of the top quark decays hadronically and the other semi-leptonically).
- Single top quark production (\( t(\bar{t})j, tW \)).
- \( W^+W^- + \) jets (\( W \rightarrow l\nu, W \rightarrow jj \)).
- \( t\bar{t}W + \) jets (when both top quarks decay hadronically and \( W \rightarrow l\nu \)) and
- \( WZ \) (with \( W \rightarrow l\nu, Z \rightarrow \nu\bar{\nu}/jj \)).

Other subdominant contributions come from \( t\bar{t} \) (where both top quarks decaying semi-leptonically), Drell Yan process (\( l^+l^- + 0,1j \)) and \( ZZ, (Z \rightarrow l^+l^-, Z \rightarrow \nu\bar{\nu}/jj) \) from misidentification of one of the leptons fail to meet the isolation cuts required to identify signal leptons or even hadronic energy mis-measurements leading to jets faking leptons. Smaller contributions may also arise from triple gauge boson production with one of the gauge boson decaying leptonically and the others hadronically. However these are negligible compared to the \( l\nu + \) jets contribution. Other indirect contributions may arise from energy mis-measurements of jets as missing energy.

In order to select one lepton + missing energy signal, we implement the following criteria for both signal and backgrounds:

- **M1**: The final state consists of a single lepton with \( p_T > 25 \) GeV and no photons.
- **M2**: Since the dominant background contributions arise from W bosons, a large cut on the transverse mass, \( M_T(l, \not{E}_T) > 150 \) GeV, where

\[
M_T(l, \not{E}_T) = \sqrt{2p_T(l)\not{E}_T(1 - \cos(\Delta \phi))}.
\]

The \( \Delta \phi \) is the azimuthal angle separation between the charged lepton \( p_T \) and \( \not{E}_T \). A large cut on \( M_T \) reduces SM background contributions from \( l\nu + 0,1 \) jet, \( WZ, WW \) and \( t\bar{t} \) substantially as compared to the signal as seen in cut flow Table 4.3 and 4.4.
• **M3**: Events with at least one b-tagged jet with $p_T > 40$ GeV are rejected in order to reduce contribution from channels involving top quarks while leaving SUSY signals mostly unaffected.

• **M4**: As seen from Figure 4.2 the weakly produced SUSY signals have a comparatively lower jet multiplicity compared to SM background processes involving strong production such as $t\bar{t}$ or single top. Thus a cut on the jet multiplicity in the signal events helps to suppress the large SM background from these sources. Thus, we demand jet multiplicity, $N_{jet} \leq 3$.

• **M5**: Since SUSY signals have a large missing energy compared to the SM background, $\not{E}_T > 100$ GeV helps to reduce contributions from background.

• **M6**: The events are made additionally quite from hadronic activity by demanding at most 1 jet in the final state. This helps to further reduce backgrounds

| Signal | Number of events after cut |
|--------|-----------------------------|
|        | Preselection(M1) | M2  | M3  | M4  | M5  | M6  |
| BP1    | 2036            | 1591| 1558| 1549| 1281| 1144|
| BP2-a  | 5031            | 3776| 3705| 3692| 2965| 2707|
| BP2-b  | 5002            | 2555| 2502| 2495| 1969| 1772|
| BP3    | 8452            | 1331| 1291| 1281| 910 | 735 |

**Table 4.3.** Mono-lepton + missing energy signal final state number of events at 100 fb$^{-1}$ for SUSY signals. Note that the events have been rounded-off to the nearest integer.
events from $t \bar{t}$ and single top production.

| SM Backgrounds | Number of events after cut |
|----------------|---------------------------|
|                | Preselection(M1) | M2 | M3 | M4 | M5 | M6 |
| $l \nu + 0, 1j$ | $8.2 \times 10^6$ | $8.36 \times 10^5$ | $8.3 \times 10^5$ | $8.28 \times 10^5$ | $4.44 \times 10^5$ | $4.22 \times 10^5$ |
| Drell Yan      | $2.74 \times 10^7$ | $2.7 \times 10^4$ | $2.6 \times 10^4$ | $4662$ | $4102$ | $2859$ |
| WW             | $5.75 \times 10^5$ | $4075$ | $3925$ | $3897$ | $951$ | $808$ |
| WZ             | $7.77 \times 10^4$ | $1.27 \times 10^4$ | $1.24 \times 10^4$ | $1.1 \times 10^4$ | $7737$ | $5753$ |
| ZZ             | $2888$ | $533$ | $526$ | $526$ | $322$ | $288$ |
| $t \bar{t}$    | $1.25 \times 10^6$ | $3.66 \times 10^4$ | $1.1 \times 10^4$ | $1.03 \times 10^4$ | $7182$ | $3926$ |
| Single top     | $3.16 \times 10^6$ | $1.6 \times 10^4$ | $6634$ | $6307$ | $2036$ | $1214$ |
| Total          |                      |     |     |     |     | $4.368 \times 10^5$ |

Table 4.4. Mono-lepton + missing energy signal final state number of events at 100 fb$^{-1}$ for SM background. Note that the events have been rounded-off to the nearest integer.

In Table 4.3 and 4.4 we list the number of events observable at 13 TeV LHC at 100 fb$^{-1}$, for the signal and SM background respectively. Although most of the SM background events could be suppressed, the continuum background from $l \nu + 0, 1j$ survives most of the cuts. The required luminosities for observing a 3σ and 5σ excess for the mono-lepton + $E_T$ channel are given in Table 4.5. The statistical significance is computed using:

$$S = \sqrt{2[(s + b)\ln(1 + \frac{s}{b}) - s]}$$  \hspace{1cm} (4.3)

where $s$ and $b$ refer to the number of signal and background events after implementing the cuts M1 – M6 respectively.

| Signal | $\mathcal{L}_{3\sigma} \ (fb^{-1})$ | $\mathcal{L}_{5\sigma} \ (fb^{-1})$ |
|--------|----------------------------------|----------------------------------|
| BP1    | 301                              | 836                              |
| BP2-a  | 54                               | 150                              |
| BP2-b  | 126                              | 349                              |
| BP3    | 729                              | 2023                             |

Table 4.5. Required luminosities for discovery of mono lepton final states with missing energy at $\sqrt{s}$ TeV LHC.

We find that the best signal significance is obtained by retaining at least one jet in the signal for all the benchmarks since the dominant background $l \nu + 0, 1j$ and signal both have only ISR jet contributions. We note that coupled with large $M_T$, $E_T$ and one jet in the final state helps to improve the signal significance. Among all the benchmarks, BP2-a has a high leptonic branching fraction for the chargino ($\sim 37\%$) and a large mass gap $\Delta M$ between the chargino and LSP. This leads to a relatively high cut efficiency for the signal and a 3σ excess can be observed $\sim 55$.
fb$^{-1}$ data at LHC. BP1, having a large $\Delta M$ but lower chargino leptonic branching fraction, i.e., $\sim 12\%$ would require $\sim 300$ fb$^{-1}$ of data for observing a $3\sigma$ excess at LHC. The relatively compressed spectra BP2-b and BP3 although with large leptonic branching fractions of the chargino, i.e. $\sim 37\%$ and $100\%$ respectively, have a lower cut efficiency owing to a smaller $\Delta M \sim 40$ GeV. Thus the lepton is soft compared to BP1 and BP2-a and hence requires a higher luminosity $\sim 130/ fb^{-1}$ and $\sim 750$ fb$^{-1}$ respectively for observation.

4.5 Di-lepton + 0 jet + $E_T$ signal

The challenge in having a multi-lepton signal from the production of electroweakinos which are higgsino-like comes from the fact that they are very close in mass. Thus their decay usually leads to soft final states. However with a sneutrino LSP and the possibility of the decay of the chargino to a hard lepton and the LSP leads to a healthy di-lepton signal with large missing energy (from $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ as well as $\tilde{\chi}^+_1 \tilde{\chi}^0_2$ pair production, provided the next-to-lightest neutralino decay yields a lepton via the chargino). A sub-dominant contribution also arises from $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ with each of the neutralino decaying to a chargino and an off-shell $W$ boson which gives soft decay products. The chargino then decays to a charged lepton and sneutrino LSP. This favorably happens when chargino is the lightest of the higgsinos. Owing to the Majorana nature of $\tilde{\chi}^0_i$ we can have signals for opposite-sign and same-sign di-lepton final states with large missing transverse energy. Hence, we look into both the possibilities:

- Opposite sign di-lepton + 0 jet + $E_T$
- Same sign di-lepton + 0 jet + $E_T$

4.5.1 Opposite Sign di-lepton + 0 jet + $E_T$ signal

Opposite sign di-lepton signal arises mainly from $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ production process. Subdominant contributions arise from $\tilde{\chi}^+_1 \tilde{\chi}^0_1$, $\tilde{\chi}^+_1 \tilde{\chi}^0_2$ and $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ as discussed before. The dominant SM contributions to the opposite sign di-lepton signal with missing energy come from $t\bar{t}$, $tW$ and Drell-Yan production. Among the di-boson processes, $W^+W^-$ ($W^+ \rightarrow l^+\nu, W^- \rightarrow l^-\bar{\nu}$), $ZZ$ ( $Z \rightarrow l^+l^-, Z \rightarrow jj/\nu\bar{\nu}$ ) and $WZ$+jets ($W \rightarrow jj, Z \rightarrow l^+l^-$) also contribute substantially to the opposite sign di-lepton channel. Triple gauge boson processes may also contribute. However they have a small production cross-section and are expected to be subdominant. There could also be fake contributions to missing energy from hadronic energy mis-measurements.

In Figure 4.4 we show the normalized distributions for several kinematic variables for two benchmarks BP2-a and BP2-b with $\Delta M = 140, 40$ GeV respectively along with the dominant SM backgrounds after selecting the opposite sign-di-lepton state (D1). We find that as expected the lepton $p_T$ distribution for BP2-a is much
harder than the SM backgrounds processes whereas for BP2-b with a lower mass gap between the chargino and LSP, the leptons are much softer and the distributions have substantial overlap with the backgrounds. We further use the other kinematic variables,

$$\not{E}_T = \sum_i p_{Ti}$$ and $$M^2_{l^+l^-} = (p_{l_1} + p_{l_2})^2$$

(4.4)

(where i runs over all visible particles in the final state) represent the transverse missing energy and invariant mass-squared of the di-lepton final state respectively which peak at higher values for SUSY signals over backgrounds in BP2-a whereas BP2-b however still retains a large overlap with the SM backgrounds. However the largest source of background for the di-lepton background coming from Drell-Yan process can be removed safely by excluding the Z boson mass window for $$M_{l^+l^-}$$. Since the SUSY signals do not arise from a resonance the exclusion of the Z mass window is expected to have very little effect on the signal events. We further note that removing b-tagged jets would also be helpful in removing SM background contributions from the strongly produced top quark channels which have huge cross sections at the LHC.

Another kinematic variable of interest to discriminate between SUSY signals and SM backgrounds is the $$M_{T_2}$$ variable [156] constructed using the leading and sub-leading lepton $$p_T$$ and $$\not{E}_T$$. For processes with genuine source of $$\not{E}_T$$ there exists a kinematic end point of $$M_{T_2}$$ which terminates near the mass of the parent particle producing the leptons and the invisible particle. In SM, channels such as $$t\bar{t}, tW, W^+W^-$$ with a W boson finally giving the massless invisible neutrino in the event, the end-point would be around 80 GeV. For SUSY events the invisible particle is not massless and therefore the visible lepton $$p_T$$ will depend on the mass difference. Thus the end-point in the signal distribution would not have a cut-off at the parent particle mass anymore. For BP2-a which has a large $$\Delta M$$ the end point is expected at larger values (~ 220) GeV. However for BP2-b, where the available phase space is small for the charged lepton due to smaller $$\Delta M$$ the $$M_{T_2}$$ distribution is not very wide and has an end-point at a much lower value. Thus a strong cut on this variable is not favorable when the sneutrino LSP mass lies close to the electroweakino’s mass.

Following the features of the kinematic distributions, we implement the following optimal selection criteria as follows for both signal and backgrounds:

- **D1**: The final state consists of two opposite sign leptons and no photons.
- **D2**: The leading lepton has $$p_T > 20$$ GeV and the sub-leading lepton has $$p_T > 10$$ GeV.
- **D3**: $$M_{l^+l^-} > 10$$ GeV helps remove contributions from photon mediated processes while the Z mass window is also removed by demanding that the opposite-sign same flavor di-lepton invariant mass satisfies $$76 < M_{l^+l^-} < 106$$ GeV. This
Figure 4.4. Normalized distributions of several kinematic variables after cut D1.

helps to reduce a large resonant contribution form the $Z$ exchange in Drell-Yan process.

- **D4**: We reject any $b$-jet by putting a $b$-jet veto (for $p_T > 40$ GeV). This helps in suppressing background events coming from top quark production.

- **D5**: We demand a completely hadronically quite event by choosing zero jet
Table 4.6. Opposite Sign di-lepton + \( \not{E}_T \) final state number of events at 100 fb\(^{-1}\) for SUSY signals. Note that the events have been rounded-off to the nearest integer.

| Signal  | Number of events after cut | Preselection (D1) | D2 | D3 | D4 | D5 | D6 | D7 | D8 |
|--------|----------------------------|-------------------|----|----|----|----|----|----|----|
| BP1    |                            | 108               | 108| 93 | 91 | 57 | 18 | 17 |    |
| BP2-a  |                            | 316               | 314| 285| 276| 185| 119| 102|    |
| BP2-b  |                            | 365               | 361| 281| 276| 184| 36 |    |    |
| BP3    |                            | 1939              | 1915| 1471| 1444| 949| 151|    |    |

| Signal  | Number of events after cut | Preselection (D1) | D2 | D3 | D4 | D5 | D6 |
|--------|----------------------------|-------------------|----|----|----|----|----|
| BP2-b  |                            | 361               | 281| 276| 184| 36 |    |    |
| BP3    |                            | 1915              | 1471| 1444| 949| 151|    |    |

- \( N_{jet} = 0 \) in the signal events. This is effective in suppressing contributions from background processes that are produced via strong interactions.

- **D6:** We demand \( \not{E}_T > 80 \) GeV to suppress the large Drell-Yan contribution.

- **D7:** We demand \( M_{T2} > 90 \) GeV which helps reduce a majority of the other the SM backgrounds.

- **D8:** \( \not{E}_T > 100 \) GeV is implemented to further reduce the SM backgrounds.

In Table 4.6 we show the signal events that survive the above listed kinematic selections (cut-flow). We find that among all benchmarks, BP2-a is the most robust. Note that we avoid using the \( M_{T2} \) cut on the benchmarks where the mass splitting between the chargino and the sneutrino LSP is small as D7 cut makes the signal events negligible. As pointed out earlier, the end-point analysis in \( M_{T2} \) is not favorable for small \( \Delta M \) as seen in the signal and background distributions in fig. 4.4. Thus BP2-b and BP3 have cuts D1-D6. In Table 4.7 we plot the SM background events after each kinematic cuts. Quite clearly up to cut D6 the SM background numbers are quite large, and then drastically reduce after the \( M_{T2} \) cut (D7) is imposed.

In Table 4.8 we give the required integrated luminosities to achieve a 3\( \sigma \) and 5\( \sigma \) statistical significance for the signal events of the four benchmark points. Just like for the mono-lepton case, BP2-a requires the least integrated luminosity and is in fact gives a 3\( \sigma \) significance for much lower luminosity compared to mono-lepton signal. However for the rest of the benchmarks mono-lepton channel is more favorable while the opposite-sign di-lepton can act as a complementary channel for BP1 with higher luminosity and BP3 with the very-high luminosity option of LHC. BP2-b type of spectrum for the model is strongly suppressed in the di-lepton channel. The signal rates can be attributed to the fact that the leptonic branching of the chargino is
much larger for BP2-a (∼ 37%) than BP1 (∼ 12%) and hence the signal is much more suppressed for BP1 than in BP2-a.

| Signal       | Number of events after cut |
|--------------|-----------------------------|
|              | Preselection (D1) | D2      | D3      | D4      | D5      | D6      | D7      | D8      |
| Drell Yan    | 9.0 × 10^7         | 8.87 × 10^7 | 6.92 × 10^6 | 6.85 × 10^6 | 5.36 × 10^6 | 394      | 228     | 41      |
| W^+W^-       | 1.03 × 10^5         | 1.02 × 10^5 | 8.1 × 10^4   | 8.08 × 10^4  | 7.16 × 10^4  | 4159     | 17      | 9       |
| ZZ           | 1.0 × 10^4          | 1.0 × 10^4  | 383       | 381     | 295     | 69       | 30      | 27      |
| WZ           | 3.0 × 10^4          | 3.0 × 10^4  | 2695      | 2600    | 776     | 46       | 3       | 2       |
| t¯t          | 3.8 × 10^5          | 3.78 × 10^5 | 3.04 × 10^5 | 9.08 × 10^4 | 2.15 × 10^4 | 16128    | 81      | 65      |
| tW           | 1.3 × 10^5          | 1.28 × 10^5 | 1.03 × 10^6 | 4.97 × 10^4 | 2.2 × 10^4  | 6016     | 84      | 38      |
| Total        |                    |          |          |          |          |          |          | 26812   | 182     |

Table 4.7. Opposite Sign di-lepton + E_T final state number of events at 100 fb^{-1} for Standard Model backgrounds. Note that the events have been rounded-off to the nearest integer.

Thus this channel is not a likely probe for benchmarks with a smaller phase space, like BP2-b and BP3 in which cases, as seen in the previous section, mono-lepton signals fare better over di-lepton signals. Whereas for spectra like BP2−a, with a large phase space available, opposite sign di-lepton signals are much more sensitive than mono-lepton signals. In contrast spectra like BP1 with a lower leptonic branching of the chargino, mono-lepton + missing energy signal is still a better channel to look for than opposite sign di-lepton channel.

| Signal | $\mathcal{L}_{3\sigma}$ (fb^{-1}) | $\mathcal{L}_{5\sigma}$ (fb^{-1}) |
|--------|----------------------------------|----------------------------------|
| BP1    | 585                              | 1624                             |
| BP2-a  | 19                               | 52                               |
| BP2-b  | $1.9 \times 10^4$                | $5.1 \times 10^4$                |
| BP3    | 1065                             | 2950                             |

Table 4.8. Required luminosities for discovery of opposite sign di-lepton + E_T final states at $\sqrt{13}$ TeV LHC.

4.5.2 Same Sign di-leptons + 0 jet + E_T signal

A more interesting and unique new physics signal at LHC in the di-lepton channel is the same-sign di-lepton mode. The same-sign di-lepton in the absence of missing transverse energy is a clear signal for lepton number violation and forms the backbone for most studies of models with heavy right-handed Majorana neutrinos. Even with missing energy, the same-sign di-lepton is a difficult final state to find within the SM and therefore a signal with very little SM background. Thus finding signal events in this channel would give very clear hints of physics beyond the SM.
### Table 4.9

| Signal | Number of events after cut: |
|--------|-----------------------------|
|        | Preselection (S1) | S2 | S3 | S4 | S5 |
| BP1    | 4               | 4  | 4  | 3  | 2  |
| BP2-a  | 25              | 23 | 23 | 17 | 11 |
| BP2-b  | 26              | 18 | 18 | 12 | 7  |
| BP3    | 2               | 0.4| 0.4| 0.2| 0.1|

Same sign di-lepton + $\not{E}_T$ final state number of events at 100 fb$^{-1}$ for SUSY signals. Note that the events have been rounded-off to the nearest integer where relevant.

In our framework of SUSY model the same-sign di-lepton signal with missing energy and few jets come from the production modes $\tilde{\chi}_1^±\tilde{\chi}_2^0$ and/or $\tilde{\chi}_1^±\tilde{\chi}_1^0$ where the lepton number violating contribution comes from the decay of the Majorana-like neutralinos given by $\tilde{\chi}_2^0 \rightarrow W^{\pm*}\tilde{\chi}_1^\pm$ with $\tilde{\chi}_1^\pm \rightarrow l\nu$. We note that same-sign di-lepton backgrounds are rare in SM, with some small contributions coming from processes such as $pp \rightarrow WZ, ZZ, W^+W^-/W^-W^-+jets, t\bar{t}W$ and $t\bar{t}Z$ as well as from triple gauge boson productions such as $WWW$ where with two of the $W$ bosons being of same sign and the other decaying hadronically. Other indirect backgrounds can arise from energy mis-measurements, i.e., when jets or photons or opposite sign leptons fake a same sign di-lepton signal.

For our analysis we select the same-sign di-lepton events using optimal cuts for both signal and background using the following kinematic criteria:

- **S1:** The final state consists of two charged leptons with same-sign and the leading lepton in $p_T$ must satisfy $p_T > 20$ GeV with the sub-leading lepton having $p_T > 15$ GeV. Additionally we ensure that there are no isolated photon and $b$-jets in the final state.

- **S2:** A minimal cut on the transverse mass constructed with the leading charged lepton ($l_1$), $M_T(l_1, \not{E}_T) > 100$ GeV is chosen to reject background contributions coming from $W$ boson.

- **S3:** To suppress background from $W^\pm W^\pm jj$ as well as those from $t\bar{t}W, t\bar{t}Z$ with higher jet multiplicities than the SUSY signal, we keep events with only up to 2 jets.

- **S4:** A large missing energy cut, $\not{E}_T > 100$ GeV is implemented to reduce SM backgrounds.

- **S5:** Finally we choose the events to be completely hadronically quite and demand zero jets in the event.
In Tables 4.9 and 4.10 we show the signal and backgrounds events after each selection cuts are imposed. As the same-sign signal is strongly constrained by existing LHC data, our benchmarks have been chosen to comply with the existing limits. Thus we find that our benchmark choices do not seem too robust in terms of signal rates, especially BP3 which has the chargino as the NLSP. It is therefore important to point out that BP1 like spectra is naturally not favored to give a same-sign di-lepton signal while BP3 is the most probable to give the same-sign signal but has been chosen to suppress the signal to respect existing constraints (by choosing very small branching for the neutralinos to decay to chargino). However the spectra as reflected by BP2-a and BP2-b satisfying existing constraints do present us with a significant number of event rates when compared to the background after cuts.

From the above cuts, we find that a large $M_T(l_1)$ cut coupled with a large $E_T$ and the requirement of jet veto removes a large fraction of the dominant WZ background as well as other fake contributions coming from $t\bar{t}$. Other genuine contributions to this channel from $W^+W^- jj$, $t\bar{t}W$ and WWW having a lower production cross-section and are efficiently suppressed by cuts on $E_T$, $M_T$ and applying a jet veto. Amongst all benchmarks, the most sensitive to the same sign di-lepton analysis are BP2-a and BP2-b where $\text{BR}(\tilde{\chi}_0^0 \rightarrow \tilde{\chi}_1^\pm W^\mp \rightarrow l\bar{\nu}) \sim 3.3\%$. Note that BP2-b, with a smaller $\Delta M$ gives soft leptons and is therefore slightly suppressed and requires larger integrated luminosity $\sim 595\text{ fb}^{-1}$ of data whereas BP2-a requires $250\text{ fb}^{-1}$ of data at LHC for observing a $3\sigma$ excess. Thus the same-sign di-lepton can be a complementary channel to observe for both benchmarks of BP-2.

| SM Backgrounds | Number of events after cut |
|-----------------|-----------------------------|
|                 | Preselection (S1) | S2 | S3 | S4 | S5 |
| $WZ$            | 1925             | 526 | 465 | 97 | 20 |
| $ZZ$            | 55               | 3   | 3   | 0.3 | 0.1 |
| $WWW$           | 37               | 18  | 13  | 4   | 0.4 |
| $W^+W^- jj$     | 273              | 115 | 77  | 37  | 1   |
| $W^-W^+ jj$     | 127              | 55  | 38  | 12  | 0.3 |
| $tW$            | 30               | 15  | 14  | 5   | 3   |
| $t\bar{t}W$     | 85               | 40  | 20  | 9   | 1   |
| $t\bar{t}$      | 56               | 40  | 31  | 17  | 4   |
| Total background|                 |     |     |     | 30  |

Table 4.10. Same sign di-lepton + $E_T$ final state number of events at 100 fb$^{-1}$ for SM background. Note that the events have been rounded-off to the nearest integer where relevant.
**Table 4.11.** Required luminosities for discovery of same sign di-lepton final states with missing energy at \(\sqrt{s} = 13\) TeV LHC.

| Signal    | \(L_{3\sigma}\) (fb\(^{-1}\)) | \(L_{5\sigma}\) (fb\(^{-1}\)) |
|-----------|-------------------------------|-------------------------------|
| BP2-a     | 250                           | 692                           |
| BP2-b     | 595                           | 1646                          |

We must again point out here that for BP3-like spectra with \(\tilde{\chi}_1^\pm\) NLSP the same-sign di-lepton would be the most sensitive channel of discovery, for large \(|\mu|\) and small \(M_2\), where the neutralino decay to chargino NLSP becomes large (see figs. 3.3 and 3.4) because of the small SM background. In such a case both \(\tilde{\chi}_1^0\) and \(\tilde{\chi}_2^0\) will decay to the NLSP along with soft jets or leptons. Thus both \(\tilde{\chi}_1^+\tilde{\chi}_1^0\) and \(\tilde{\chi}_2^+\tilde{\chi}_2^0\) production channels would have contributed to the signal leading to a two-fold increase of the number of signal events and would be more sensitive to detect a sneutrino LSP scenario.

We conclude that conventional channels such as mono-lepton or opposite sign di-lepton channels however with low hadronic activity, i.e, with at most 1 jet or no jet would be extremely useful channels to look for cases of a sneutrino LSP. Detecting same sign di-lepton signals at higher luminosities would further serve as a strong confirmatory channel for a sneutrino LSP scenario over a \(\tilde{\chi}_1^0\) LSP scenario as in the MSSM from the compressed higgsino sector and can exclude large portions of the \(M_1 < 0\) parameter space.

**Dependence on flavor of \(\tilde{\nu}_R\) LSP**

LHC searches explore different search channels involving the flavor of the leptons owing to their high reconstruction efficiency at the detector, for instance, \(e + \not{E}_T\), \(\mu + \not{E}_T\) [136, 137], \(ee/\mu\mu/e\mu\) final states associated with \(\not{E}_T\) [134, 135]. As we have considered both first and second generation sneutrinos to be light in this study, we qualitatively analyze the prospects of the signals studied by tagging the flavor of the leptons as well as consequences of a single light generation of sneutrino LSP assuming the net leptonic branching to be the same in both cases.\(^6\) Hence, for a single light sneutrino LSP, the observed events in the mono-lepton and di-lepton signals contribute to only a single choice of lepton flavor and vanishes for the rest. We compare the signal and background in this case for the same luminosity as before and comment on the results obtained for our benchmarks.

For *mono-lepton* signals with degenerate sneutrino LSP (first two generations), say, we look at only an electron in the final state. This would lead to reduction of

\(^6\)This may not correspond to the same parameter point since the presence of the other decay modes of \(\tilde{\chi}_1^\pm\) affect the leptonic branching for the single light sneutrino LSP case. However, when \(\tilde{\chi}_1^\pm\) is the NLSP, the net leptonic branching is the same in both cases.
both signal and background in Table 4.3 and 4.4 by half such that the significance falls by a factor of \(\sqrt{2}\). If a single generation of right sneutrino was light, say \(\tilde{\nu}_e\), then only the background would reduce by a factor \(1/2\). Since the signal remains unchanged as the chargino now decays completely to an electron and the lightest sneutrino the signal significance increases by a factor of \(\sqrt{2}\). Consequently no signal is observed for the other flavor lepton channel, in this case \(\mu\), where although the background decreases by half, no signal events are present.

For the di-lepton signal there are three possible channels \(ee, \mu\mu\) and \(e\mu\) with net branching fraction of around \(1/4, 1/4\) and \(1/2\) respectively. We consider first the opposite-sign di-lepton channel. For \(e\mu\) final states, only different flavor lepton backgrounds such as from \(WW, t\bar{t}\) or \(tW\) contribute with a BR \(\simeq 2/3\). However contributions from same flavor di-lepton sources such as involving \(Z\) boson fall. The total background thus reduces to nearly 70%. Since signal in this channel also reduces to half thereby the significance falls. For channels with same flavor (SF) leptons, i.e, \(ee/\mu\mu\), dominant SF contributions are from \(Z\) boson whereas sub-dominant contributions from top quark production channel reduce. Although SM background reduces so does the signal statistics and hence the significance. However, in presence of a single generation of light sneutrino we find that the signal significance improves by a factor of \(\sqrt{2}\). Note that if the LSP is \(\tilde{\nu}_e\) then the chargino decays to an electron and the LSP. Therefore \(ee + E_T\) channel significance improves whereas \(\mu\mu\) and \(e\mu\) channels vanish. Similarly, for an \(\tilde{\nu}_\mu\) LSP, \(\mu\mu + E_T\) channels improve whereas the rest vanish. Similar conclusions may be drawn for same sign di-lepton channel, where the dominant backgrounds are \(WZ\) and \(W^\pm W^\pm\), the significance is expected to improve only for a single light generation of sneutrinos.

Some comments on the prospect of \(\tau\) flavor searches and other channels

In this context, we also explore the discovery prospects of a natural higgsino sector and a single light \(\tilde{\nu}_\tau\) as the LSP. LHC has looked at final states with tau leptons, decaying hadronically, in the context of electroweakino searches. The electroweakino mass limits considerably reduce for tau lepton searches owing to the reduced reconstruction efficiency of hadronically decaying \(\tau\) leptons (\(\sim 60\%\)) [157] compared to that of the light leptons (\(e, \mu\)) (\(\sim 95\%\)). From searches with one or two hadronically decaying tau leptons associated with light leptons lead to stronger limits from \(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2\) production on \(m_{\tilde{\chi}^1_1}, m_{\tilde{\chi}^0_2} > 800/1000\) GeV for a bino-like \(m_{\tilde{\chi}^1_1} < 200\) GeV depending on the masses of the intermediate sleptons [133]. Limits on electroweakino searches from three tau lepton searches exclude wino-like degenerate \(m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^1_1} > 600\) GeV for a bino-like \(m_{\tilde{\chi}^1_1} < 200\) GeV [133]. Limits from opposite sign tau lepton searches [158] reinterpreted from \(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2\) production and decaying via intermediate sleptons lead to \(m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^1_1} > 760\) GeV for \(m_{\tilde{\chi}^1_1} < 200\) GeV. From opposite sign di-tau searches reinterpreted in context of chargino pair production [158] leads to a bound close to 650 GeV on chargino for LSP masses up to 100 GeV.
For the current scenario of a compressed electroweakino sector in presence of a light $\tilde{\nu}_\tau$ LSP, the signals from the low-lying compressed higgsino sector would be:

- Mono-$\tau$ jet + $E_T$
- Di $\tau$ jets + $E_T$

For the mono-$\tau$ channel, both signal and background scale by the tau reconstruction efficiency, $\epsilon_R = 0.6$ is the tau reconstruction efficiency. Further a factor of $\frac{1}{2}$ comes in for the background since the branching of $W$ or $Z$ boson to light leptons is roughly twice that to the tau lepton as for a $\tilde{\nu}_{e/\mu}$ LSP. However owing to the reduced tau reconstruction efficiency, the signal significance falls by $\sim \sqrt{\epsilon_R} \sim 0.78$. Similarly, for the di-$\tau$ channels, the significance scales by $\epsilon_R \sim 0.6$. Hence, the estimated reach of the higgsino mass parameter, $\mu$ is expected to weaken for a $\tilde{\nu}_\tau$ LSP compared to $\tilde{\nu}_{e/\mu}$ LSP.

Note that, the pionic decay modes of the $\tilde{\chi}_1^+\chi_2^0$ and $\chi_2^0 \chi_3^0$ can dominate among the hadronic modes as the respective mass differences become less than about a GeV. While we have used form factors to estimate the pionic branching fractions, we have not considered the possibility of late decay into pions in this work. This is because we have ensured that in the parameter space of our interest the two body mode to the lightest sneutrino(s) always remain prompt. Further, the potential of the loop-induced channel $\tilde{\chi}_{02} \rightarrow \tilde{\chi}_{01} \gamma$ in deciphering the scenario has not been explored in the present work. While the photons, thus produced in the cascade, would be soft in the rest frame of $\tilde{\chi}_{02}^0$, it may be possible to tag hard photons in the CM frame. Note that the choice of light higgsinos are motivated by “naturalness” at the electroweak scale and we do not discuss the discovery potential for stop squarks and gluino in the present work which we plan to do in a subsequent extension.

### 5 Conclusion

To summarize, motivated by “naturalness” criteria at the electroweak scale, we have studied a simplified scenario with low $\mu$ parameter in the presence of a right-sneutrino LSP. For simplicity, we have assumed the gaugino mass parameters to be quite heavy $\gtrsim 1$ TeV. In such a scenario, with $O(100)$ GeV Majorana mass parameter the sneutrino Yukawa coupling can be as large as $10^{-6} - 10^{-7}$. In contrast with the MSSM with light-higgsinos, in the present context, the higgsino-like states can decay to the sneutrino LSP. While the neutral higgsinos can decay into neutrino and sneutrino, the lightest chargino can decay into a lepton and sneutrino. We have demonstrated that the latter decay channel can lead to various leptonic final states with up to two leptons (i.e. mono-lepton, same-sign di-lepton and opposite-sign di-lepton) and missing transverse energy at the LHC, which can be important in searching for or constraining this scenario. We have only considered prompt decay into leptons, which
require \( y_\nu > 10^{-7} \) and/or small \( \mathcal{O}(10^{-3}) \) left-right mixing in the sneutrino sector. For smaller values of \( y_\nu \), contribution from the latter dominates and the leptonic partial width on small gaugino-higgsino mixing (\( \lesssim \mathcal{O}(10^{-2}) \)). Further, the mass split between the three states, the lightest chargino and the two lightest neutralinos depend on the choice of the gaugino mass parameters, as well as on one-loop contributions. We have shown how these mass differences significantly affect the three-body partial widths, thus affecting the branching ratios to the sneutrino. Therefore, even assuming the gaugino-like states to be above a TeV, as in our benchmark scenarios, the viability of a low \( \mu \) parameter depends crucially on the choice of \( M_1, M_2 \). This has been emphasized in great detail. Consequently, there are regions of the parameter space where \( BR(\tilde{\chi}_1^\pm \rightarrow l\tilde{\nu}) \sim 100\% \) especially in the negative \( M_1 \) parameter space. Such regions of parameter space would lead to enhanced leptonic rates, thereby a large fraction of negative \( M_1 \) parameter space can be excluded from current leptonic searches at LHC. We check for a given \( |\mu| \) the existing constraints by recasting our signal in CheckMATE against existing LHC analysis relevant for our model parameters to search for a viable parameter region of the model. We then choose four representative benchmarks and observe that mono-lepton signals with large \( E_T \) and little hadronic activity could successfully probe \( \mu \) as low as 300 GeV at the ongoing run of LHC with \( \sim 150 \text{ fb}^{-1} \) of data at 5\( \sigma \). Additional confirmatory channels for the \( \tilde{\nu} \) LSP scenario are opposite-sign di-lepton and same-sign di-lepton signal which require \( \sim 50 \text{ fb}^{-1} \) and \( \sim 690 \text{ fb}^{-1} \) for 5\( \sigma \) discovery at LHC. While our benchmarks assume the first two generations of sneutrinos to be degenerate and consider only e, \( \mu \) for the charged leptons which can be detected efficiently at the LHC, the reach may be substantially reduced if only tau- sneutrino appears as the lightest flavor due to the low tau reconstruction efficiency.

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