Flavored co-annihilations

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Abstract: Neutralino dark matter in supersymmetric models is revisited in the presence of flavor violation in the soft supersymmetry breaking sector. We focus on flavor violation in the sleptonic sector and study the implications for the co-annihilation regions. Flavor violation is introduced by a single $\tilde{\mu}_R - \tilde{\tau}_R$ insertion in the slepton mass matrix. Limits on this insertion from BR($\tau \rightarrow \mu + \gamma$) are weak in some regions of the parameter space where cancellations happen within the amplitudes. We look for overlaps in parameter space where both the co-annihilation condition as well as the cancellations within the amplitudes occur. In mSUGRA, such overlap regions are not existent, whereas they are present in models with non-universal Higgs boundary conditions (NUHM). The effect of flavor violation is two fold: (a) it shifts the co-annihilation regions towards lighter neutralino masses (b) the co-annihilation cross sections would be modified with the inclusion of flavor violating diagrams which can contribute significantly. Even if flavor violation is within the presently allowed limits, this is sufficient to modify the thermally averaged cross-sections by about (10–15)% in mSUGRA and (20–30)% in NUHM, depending on the parameter space. In the overlap regions, the flavor violating cross sections become comparable and in some cases even dominant to the flavor conserving ones. A comparative study of the channels is presented for mSUGRA and NUHM cases.

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1 Introduction

Supersymmetric standard models have a natural dark matter candidate namely, the lightest supersymmetric particle (LSP) if R-parity is conserved [1]. In mSUGRA/CMSSM models, the LSP typically is the lightest neutralino [2–4]. In most of mSUGRA /CMSSM parameter space, the lightest neutralino is mostly a bino (\( B^0 \)); the bino component being close to 99%. With the bino cross-section being small, the neutralinos are overproduced resulting in a larger dark matter relic density compared to WMAP [5] allowed range. There are however, some special regions in the mSUGRA parameter space where the neutralino is able\(^1\) to satisfy the relic density limits [7, 8]. These are the (i) Bulk region, (ii) Stop (\( \tilde{t} \)) co-annihilation region, (iii) Stau (\( \tilde{\tau} \)) co-annihilation region, (iv) A-pole funnel region and (v) 

\(^1\)See also ref. [6].
Focus point/ Hyperbolic branch regions. The various processes which play an important role in each of these sub-cases is shown in figure 1.

The stau-co-annihilation region requires the mass of the lightest stau, $\tilde{\tau}_1$ to be close to the mass of the LSP. The stop-co-annihilation is typically realized with large $A$-terms, which is also the case with the bulk region [10]. Among the above depicted regions, discounting the case of large $A$-terms, $\tilde{\tau}$-co-annihilation and the focus point regions are most sensitive to pre-GUT scale effects and the see-saw mechanism [9, 11–15]. It has been shown that the co-annihilation region gets completely modified in the SU(5) GUT theory and leads to upper bounds in the neutralino masses [9]. Similarly, in the presence of type I, type II or type III see-saw mechanisms [9, 11, 14, 15] $\tilde{\tau}$-co-annihilation regions get completely modified. Strong implications can also be felt in the focus point regions unless the right handed neutrino masses are larger than the GUT scale [11]. GUT scale effects can even revive no-scale models [16]. It has also been shown that in the presence of large $A$-terms ‘new’ regions with $\tilde{\tau}$-co-annihilation appear [9, 17].

In the present work, we consider flavor violation in the sleptonic sector and study its implications for the co-annihilation regions. In generic MSSM, flavor violation can appear either in the left handed slepton sector (LL), right handed slepton sector (RR) or left-right mixing sector (LR/RL) of the sleptonic mass matrix. However, we concentrate on the flavor violation in RR sector as it has some interesting properties related to cancellations in the lepton flavor violating amplitudes as discussed below. Such flavor mixing is not difficult to imagine. It appears generically in most supersymmetric grand unified theories. A classic example is the SUSY SU(5) GUT model. If the supersymmetry breaking soft terms are considered universal at scales much above the gauge coupling unification scale ($M_{GUT}$), typically the Planck scale, then the running of the soft terms between the Planck scale and the GUT scale could generate the RR flavor violating entries in the sleptonic sector [18, 19].
For demonstration purposes, let’s consider the superpotential of the SU(5) SUSY-GUT:

\[ W = h_{ij}^u \mathbf{10}_i \mathbf{10}_j \bar{5}_H + h_{ij}^d \mathbf{10}_i \bar{5}_j 5_H + \cdots \]  

(1.1)

where \( \mathbf{10} \) contains \( \{q, \bar{c}, e^c\} \) and \( \bar{5} \) contains \( \{\bar{d}, l\} \). As supersymmetry is broken above the GUT scale, the soft terms receive RG (renormalisation group) corrections between the high scale \( M_X \) and \( M_{\text{GUT}} \), which can be estimated using the leading log solution of the relevant RG equation. For example, the soft mass of \( \mathbf{10} \) would receive corrections:

\[ \Delta_{ij}^{RR} = (m^2_{10})_{ij} \approx -\frac{3}{16\pi^2} h_i^t V_{ij} (3m_0^2 + A_0^2) \log \left( \frac{M_X^2}{M_{\text{GUT}}^2} \right), \]  

(1.2)

where \( V_{ij} \) stands for the \( ij \)th element of the CKM matrix. Since \( \mathbf{10} \) contains \( e^c \), the flavor violation in the CKM matrix (in the basis where charged leptons and down quarks are diagonal) now appears in the right handed slepton sector. Below the GUT scale, the RG scaling of the soft masses just follows the standard mSUGRA evolution and no further flavor violation is generated in the slepton sector in the absence of right handed neutrinos or any other seesaw mechanism. Assuming \( M_X \approx 10^{18} \) GeV, the leading log estimates of the ratios of flavor violating entries to the flavor conserving ones, \( \delta_{ij}^{RR} \equiv \Delta_{ij}^{RR} / m_{ij}^2 \), are given in the table 1. We have taken \( A_0 = 0 \) and \( h_t \approx 1 \). At 1-loop level \( \delta \) it is roughly independent of \( m_0 \).

From the table 1, we see that the RG generated \( \delta_{ij}^{RR} \) is typically of \( \mathcal{O}(10^{-3} - 10^{-5}) \). Such small values will not have any implications on the co-annihilation regions or rare flavor violating decays. While non-universality at the GUT scale in this case is RG induced, there are models where non-universal soft terms can arise from non-trivial Kähler metrics in supergravity, this could be the case in models with flavor symmetry at the high scale à la Froggatt-Nielsen models (see for example, discussions in [20–26]). In such cases, the \( \delta_{RR} \)'s could be much larger, even close to \( \mathcal{O}(1) \). These terms would then receive little corrections through RG as they are evolved from the GUT scale to the electroweak scale. Recently, in an interesting paper [27], supersymmetric models with Left-Right symmetry have been studied with particular emphasis on leptonic flavor violation. In these models, both left handed and right handed slepton sectors have flavor violation with the constraint that \( \delta_{RR}(\Lambda_r) = \delta_{LL}(\Lambda_r) \), where \( \Lambda_r \) is the left right symmetry breaking scale. In such cases it could be possible to generate \( \delta_{RR} \sim \mathcal{O}(10^{-1}) \).

In this present work, we will follow a model-independent approach and assume the presence of a single flavor violating parameter \( \Delta_{\mu\tau}^{RR} \) and study the implications of it for the co-annihilation region. We will consider the simplistic case of universal soft-masses at the \( M_{\text{GUT}} \) scale with non-zero \( \delta_{23}^{RR} \) which is treated as a free parameter. To distinguish from the standard mSUGRA model, we will call this model \( \delta \)-mSUGRA and similar nomenclature also holds for the other supersymmetry breaking models which we consider in this work.

While flavor violating entries in the slepton mass matrices are strongly constrained in general, the constraints on leptonic \( \delta_{23}^{RR} \) entries are weak in some regions of the parameter

\(^2m_\tilde{l}^2 \) is the flavor conserving average slepton mass.

\(^3\)Subsequent to the appearance to this work on arXiv flavored co-annihilations have been studied by the group [28].
space [29–31]. This leads to the possibility that large flavor violation could be present in the sleptonic right handed sector. In these regions cancellations happen between various contributions to the lepton flavor violating (LFV) amplitudes. If such cancellation regions overlap with regions where sleptonic co-annihilations are important, flavor violation has to be considered in evaluating the co-annihilation cross-sections in the early universe. This is the basic point of the paper where we show that flavor violating processes can play a dominant role in the co-annihilation regions of the supersymmetric breaking soft parameter space. The processes contributing to relic density in these regions are called flavored co-annihilations.

It turns out that with mSUGRA/CMSSM boundary conditions, the parameter space where the flavor violating constraints are relaxed does not overlap with the $\tilde{\tau}_1$ co-annihilation regions unless one considers extremely large values of $\delta \gtrsim 0.8$. The overlap is not very significant and is mostly ruled out by other phenomenological constraints. However, if one relaxes the complete universality in the Higgs sector i.e., within non-universal Higgs mass models (NUHM), there is an overlap between these regions, paving way for large flavor violation to coexist with co-annihilation regions.

The fact that in $\delta$-NUHM these regions do overlap has already been observed independently by Hisano et al. [32, 33]. However, they have studied $\mu \rightarrow e \gamma$ transitions and their co-annihilating partner is not really a mixed flavor state. Further, they have not studied the relic density regions in detail.

In this present work we elaborate on these regions and study the consequences of it. The rest of the paper is organized as follows: In section 2 we discuss the effect on $\delta$ in the co-annihilation regions both in the mass of the co-annihilating partner and in the cross section. We also show that overlap between regions of LFV cancellations and co-annihilations are not possible in $\delta$-mSUGRA. In section 3 we show that in $\delta$-NUHM regions do exist where flavored co-annihilations become important. Relative importance of various cross-sections in the flavored co-annihilation regions is elaborated in section 4. We close with a summary and brief implications for LHC in section 5. In appendix A we have written down the approximate expression of the soft-masses for mSUGRA and NUHM scenario for three different values to $\tan \beta$. In appendix B we present $\delta$-mSUGRA in more detail using approximate results. Description of numerical packages used and numerical procedures followed are in appendix C. In appendix D, we present loop functions which are relevant to the discussion in the text. In appendix E we present the analytic form of the cross-sections for some scattering processes relevant for the present discussions.
2 Co-annihilation with flavor violation

Co-annihilations play an important role in reducing the (relic) number density of the dark matter particle by increasing its interactions at the decoupling point. It requires having another particle which is almost degenerate in mass with the dark matter particle and should share a quantum number with it [34]. In mSUGRA, \( \tilde{\chi}_1^0 \) can have co-annihilations with \( \tilde{\tau}_1 \) in regions of the parameter space where \( m_{\tilde{\tau}_1} \approx m_{\tilde{\chi}_1^0} \). We will now generalize this condition\(^4\) in the presence of flavor violation. As discussed in the introduction, we will consider a single \( \mu - \tau \) flavor mixing term in the RR sector, \( \Delta_{\mu \tau}^{\mu \tau} \) to be present at the weak scale. Similar analysis also holds for the \( e - \tau \) flavor mixing. The slepton mass matrix is defined by

\[
\mathcal{L}_{\text{int}} \supset - \frac{1}{2} \Phi^T M_\tilde{l}^2 \Phi
\]

where \( \Phi = \{ \tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R \} \) and

\[
M_\tilde{l}^2 = \begin{pmatrix}
    m_{\tilde{e}_L}^2 & 0 & 0 & m_{\tilde{e}_{LR}}^2 & 0 & 0 \\
    0 & m_{\tilde{\mu}_L}^2 & 0 & 0 & m_{\tilde{\mu}_{LR}}^2 & 0 \\
    0 & 0 & m_{\tilde{\tau}_L}^2 & 0 & 0 & m_{\tilde{\tau}_{LR}}^2 \\
    m_{\tilde{e}_{LR}}^2 & 0 & 0 & m_{\tilde{e}_R}^2 & 0 & 0 \\
    0 & m_{\tilde{\mu}_{LR}}^2 & 0 & 0 & m_{\tilde{\mu}_R}^2 & \Delta_{\mu \tau}^{\mu \tau} \\
    0 & 0 & m_{\tilde{\tau}_{LR}}^2 & 0 & \Delta_{\mu \tau}^{\mu \tau} & m_{\tilde{\tau}_R}^2 \\
\end{pmatrix}
\]

where, \( m_{\tilde{f}_{LR}}^2 = m_f (A_f - \mu \tan \beta)'s \) are the flavor conserving left-right mixing term, \( m_{\tilde{f}_L}^2 \)'s are the left handed slepton mass term and \( m_{\tilde{f}_R}^2 \)'s denote the right handed slepton masses.

In the limit of vanishing electron mass\(^5\) and zero flavor mixing in the selectron sector, we can consider the following reduced \( 4 \times 4 \) mass matrix. This matrix is sufficient and convenient to understand most of the discussion in the paper. It is given by

\[
M_\tilde{l}^2 = \begin{pmatrix}
    m_{\tilde{\mu}_L}^2 & 0 & 0 & m_{\tilde{\mu}_{LR}}^2 & 0 & 0 \\
    0 & m_{\tilde{\tau}_L}^2 & 0 & 0 & m_{\tilde{\tau}_{LR}}^2 & \Delta_{\mu \tau}^{\mu \tau} \\
    m_{\tilde{\mu}_{LR}}^2 & 0 & m_{\tilde{\mu}_R}^2 & \Delta_{\mu \tau}^{\mu \tau} & m_{\tilde{\tau}_R}^2 \\
    0 & m_{\tilde{\tau}_{LR}}^2 & 0 & \Delta_{\mu \tau}^{\mu \tau} & m_{\tilde{\tau}_R}^2 \\
\end{pmatrix}
\]

where, we have taken it to be real for simplicity. The lightest eigenvalue of the above matrix can be easily estimated. The lower \( 2 \times 2 \) block can be diagonalized assuming that the flavor violating \( \Delta_{\mu \tau}^{\mu \tau} \) is much smaller than the flavor diagonal entries. A second diagonalization for the stau LR mixing entry can be done in a similar manner. This leads to a rough estimate of the lightest eigenvalue as:

\[
m_{\tilde{l}_1}^2 \simeq m_{\tilde{\tau}_R}^2 (1 - \delta) - m_{\tau \mu} \tan \beta,
\]

\(^4\)The condition can be more accurately expressed as \( m_{\tilde{\chi}_1} = m_{\tilde{\chi}_1} + \delta m \), where \( \delta m \) lies within 10–15 GeV.

\(^5\)In all our numerical calculations, we have used the full \( 6 \times 6 \) mass matrix without any approximations. This approximation is valid only in models with universal scalar masses, like mSUGRA, NUHM etc.
where $\delta = \frac{\Delta_{\mu \tau}^{\nu_R}}{\sqrt{m_{\tilde{\tau}_R}^2 - m_{\tilde{\mu}_R}^2}}$. Requiring that the lightest eigenvalue not to be tachyonic, we find an upper bound on $\delta$ as follows:

$$\delta < 1 - \frac{m_{\tau} \mu \tan \beta}{m_{\tilde{\tau}_R}^2} \quad (2.5)$$

This condition becomes important in regions of the parameter space where $\mu \gg m_{\tilde{\tau}_R}^2$ and in regions where $\tan \beta$ is very large such that the second term approaches unity. For co-annihilations, $\delta$ lowers the lightest eigenvalue of the sleptonic mass matrix. Non-zero $\delta$ shifts the ‘standard regions’ in mSUGRA towards lower values of $M_{1/2}$, for a fixed $m_0$. In other words, since the sleptons become lighter, the co-annihilations happen with lighter neutralino masses. To illustrate this point let us consider mSUGRA like universal boundary conditions at the GUT scale. The one exception to the universality of the scalar mass terms particularly slepton mass terms at GUT scale is in terms of the flavor violating mass term ($\Delta_{\mu \tau}^{\nu_R}$). We will call this model as $\delta$-mSUGRA. Given that the $\Delta_{\mu \tau}^{\nu_R}$ parameter does not run significantly under RG corrections, we can use the MSSM RGE with mSUGRA boundary conditions to study the low energy phenomenology. In appendix A.1, we have presented approximate solutions for the RGE of soft masses and couplings in mSUGRA. Using approximate formulae, in figure 2 we have plotted, the $\tilde{\tau}$–co-annihilation condition, $m_{\tilde{\chi}_1^0} - m_{\tilde{\tau}_1} \simeq 0$, with and without flavor mixing. We have chosen $\delta = 0, 0.5$ and $\tan \beta = 5$. As expected from the eq. (2.4), the presence of flavor violating $\delta$ shifts the co-annihilation regions more towards the diagonal in the $m_0 - M_1$ plane. In table 2, we show the spectrum for two points with $\delta = 0$ and $\delta = 0.5$ which demonstrate that for fixed $m_0$, a lighter neutralino can be degenerate with $m_{\tilde{\tau}_1}$ in the presence of $\delta$.

6This is true as long as we stick to MSSM like particle spectrum and interactions. Additional interactions and particles can modify the flavor structure.
Eq. (2.4) is a rough estimate and not valid for large $\delta$. A more accurate expression is presented in appendix B. As we will see, this will not change the conclusions of the present discussion much. We will revisit this point again in the next section.

The presence of $\delta$ also affects the relic density computations in the co-annihilation regions. The thermally averaged cross section on which relic density crucially depends can get significantly modified with $\delta$, where flavor violating scatterings are also now allowed. The typical $\tilde{\tau}$ co-annihilation processes in the absence of flavor violation are $\chi_1^0\chi_1^0 \to \tau\tau, \mu\bar{\mu}, e\bar{e}$, $\chi_1^0\tilde{\tau}_1 \to \tau\gamma$, $\tilde{\tau}_1\tilde{\tau}_1 \to \tau\tau$, $\chi_1^0\tilde{\tau}_1 \to Z\tau$, $\tilde{\tau}_1\tilde{\tau}_1^* \to \gamma\gamma$. In the presence of $\tilde{\mu} - \tilde{\tau}$ flavor mixing, the new vertices related to flavor mixing would contribute to the processes with flavor violating final states. The corresponding Feynman diagrams are shown in figure 3, where $\mu/\tau$ would mean that the final state could either be a $\mu$ or a $\tau$. The relevant Boltzmann equations for the neutralino and the lightest slepton ($\tilde{l}_1$), continue to remain as in the unflavored co-annihilation case, though the masses and the cross-sections appearing in them change.

We have computed all the possible co-annihilation channels including flavor violation by adding the flavor violating couplings in the MSSM model file of well known relic density calculator, MicrOMEGAs \[35\]. The flavor violating co-annihilations contribute significantly to the total cross section and their relative importance increases with increasing $\delta$ as expected. So far we have not addressed the question whether such large flavor violating entries in the slepton mass matrix are compatible with the existing flavor violating constraints from rare decay processes like $\tau \to \mu + \gamma$ or $\tau \to \mu e e$ etc. Constraints from such processes have been discussed in several works. The constraints on right handed (RR) flavor violating sector are different compared to those of left handed (LL) sector as they only have neutralino contributions and have no chargino contributions. Furthermore the two neutralino contributions\(^7\) can have cancellations amongst each other in certain regions of the parameter space as elaborated in refs. [29–31]. Following \[30\], the branching ratio for $\tau \to \mu + \gamma$ can be written as in the generalized mass insertion approximation

$$
\text{BR}(\tau \to \mu\gamma) = 5.78 \times 10^{-5} \frac{M_W^4}{|\mu|^2} \frac{M_1^2 \tan^2 \beta}{|\mu|^2} \times |\delta_{23}^{RR}(I_{B,R} - I_R)|^2,
$$

where $I_{B,R}$ and $I_R$ are loop functions are given in appendix D.

\(^7\)These are the pure $\tilde{B}^0$ and the mixed $\tilde{B}^0 - \tilde{H}^0$ diagrams, as depicted in figure 4.
Figure 3. Co-annihilation channels appearing in the $\Omega_{DM}$ calculation with $\mu - \tau$ flavor violation in the right handed sector. Notice that there are now new final states where either $\mu$ or a $\tau$ could appear.

This amplitude is resultant from the two diagrams shown in the mass-insertion approximation in figure 4. The first one is a pure Bino ($\tilde{B}^0$) contribution whereas the second one is a mixed Bino-Higgsino ($\tilde{B} - \tilde{H}^0_1 - \tilde{H}^0_2$) contribution. There is a relative sign difference between these two contributions and thus leads to cancellations in some regions of the parameter space. In $\delta$-mSUGRA, these cancellations occur when $m_{\tilde{\tau}} \approx 6M_1$ or equivalently $\mu^2 \approx m_{\tilde{\tau}}^2$ [30]. In regions outside the cancellation region the limit on $\delta_{RR}$ is of $O(10^{-1})$ for $\tan \beta = 10$ and for a slepton mass of around 400 GeV [36] using the present on $BR(\tau \rightarrow \mu + \gamma) \leq 4.4 \times 10^{-8}$ [37]. In the cancellation region however the bound on $\delta$ is very weak and $\delta$ could be $O(1)$.

A large $\delta \sim O(1)$, would increase the flavor violating cross sections in the early universe. The current bounds already push the value of $\delta \sim 10^{-1}$ for reasonable values of slepton mass $\sim 400$ GeV and $\tan \beta \sim 10$. We look for regions where the bound is significantly weakened due to cancellations. This would require that there should be significant amount of cancellations among the flavor violating amplitudes to escape the bound from $\tau \rightarrow \mu + \gamma$. In figure 5, we have presented the numerical results for mSUGRA with each panel representing a different value of $\delta$ (0.2, 0.4, 0.6 and 0.8). $\tan \beta$ is fixed to be 20 and sign($\mu$) is positive. The details of the numerical procedures we have followed are presented.

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*By definition $\delta$ cannot be larger than 1. Here $O(1)$ means close to 1.
Figure 4. $\tilde{B}^0$ and $\tilde{B}^0 - \tilde{H}^0$ contribution in RR-insertion. The photon can be attached with the charged internal lines.

Figure 5. $m_0 - M_A$ plane in $\delta$-mSUGRA. The different contour shows branching ratio, $\text{BR}(\tau \rightarrow \mu \gamma)$ for $\delta = 0.2, 0.4, 0.6$ and $0.8$ (from top left clockwise) and for $\tan \beta = 20, A_0 = 0$ and sign($\mu$) > 0. The blue line indicates WMAP bound satisfied region. The black shaded region is excluded by direct search in LEP for the Higgs boson. The violet dots represent the present limits form LHC [38]. The red dot-dashed line indicates 1 TeV contour for gluino and blue dotted line marks the 1 TeV contours for first generation squark mass. The regions where the contours of $\text{BR}(\tau \rightarrow \mu \gamma)$ reaches $\lesssim 10^{-10}$ are the places where cancellations happen. In this region $\delta_{RR}^{33}$ becomes unbounded because of the cancellation between the $\tilde{B}^0$ and $\tilde{B}^0 - \tilde{H}^0$ diagrams in figure 4.
in appendix C. In all these plots, we have shown contours of $\text{BR}(\tau \rightarrow \mu \gamma)$ and the co-annihilation regions. The other constraints shown on the plot include, the purple region which is excluded as the LSP is charged, $(m_{\tilde{l}_1} < m_{\chi_1^0})$; the translucent black shaded region is excluded by search for a light neutral higgs boson at LEP, $m_h < 114.5$ GeV, the light green region where the chargino mass is excluded by Tevatron, $m_{\chi^\pm_1} < 103.5$ GeV. The co-annihilation region has been computed including the flavor violating diagrams in the thermally averaged cross-sections. The relic density is fixed by the recent 7-year data of WMAP which sets it to be [5],

$$\Omega_{CDM} h^2 = 0.1109 \pm 0.0056$$  \hspace{1cm} (2.7)

In the blue shaded region the neutralino relic density ($\Omega_{DM}$) is within the $3\sigma$ limit of [5], i.e., we require it to be

$$0.09 \leq \Omega_{DM} h^2 \leq 0.12.$$  \hspace{1cm} (2.8)

From the first panel of the figure, for $\delta = 0.2$ we see that there is no overlap in the regions where cancellation in the amplitudes for $\tau \rightarrow \mu + \gamma$ happens (around $\text{BR}(\tau \rightarrow \mu \gamma) \lesssim 10^{-10}$) and the co-annihilation region (blue region). With increasing $\delta$, as can be seen from subsequent panels, the co-annihilation region moves towards the diagonal of the plane as the slepton mass becomes lighter, and the cancellation region which requires $m_{\tilde{\tau}_R} \approx 6 M_1$ also moves towards the diagonal with increasing $\delta$. However, within $\delta$-mSUGRA these two regions do not coincide except partially at the top end of the spectrum close to the upper bound of the the co-annihilation region.

From figure 5 we can see that a very large ($\delta_{RR}^{23} \gtrsim 0.8$) is required to make the cancellation region consistent with the co-annihilation region. In $\delta$-mSUGRA having such large $\delta$ is consistent only very specific points of the parameter space (please see appendix B for more discussion). Hence, we can infer from the above figures that within the $\delta$-mSUGRA scenario the cancellation and co-annihilation region are disparate and no simultaneous solution exists. While the present discussion was based on numerical solutions for a particular $\tan \beta$, one can easily convince oneself that it would be true for any $\tan \beta$ by looking at the analytical formulæ. In fact, in the co-annihilation region, the branching fraction can be evaluated in the limit ($m_{\tilde{\tau}_R} \rightarrow M_1$) and is given as

$$\text{BR}(\tau \rightarrow \mu \gamma) \approx 1.134 \times 10^{-6} \times \frac{M_W^4 |\delta_{23}^{RR}|^2 \tan^2 \beta}{M_1^4}$$  \hspace{1cm} (2.9)

where, we have used $|\mu|^2 \approx 0.5 m_{\tilde{\tau}_R}^2 + 20 M_1^2$ and $m_{\tilde{\tau}_L}^2 \approx m_{\tilde{\tau}_R}^2 + 2.5 M_1^2$. It is important to note that, the above expression obviously does not permit any cancellations. Thus within $\delta$-mSUGRA, flavor violation in the co-annihilation region even if present would be constrained by the existing leptonic flavor violating constraints. In the following we see that this situation is no longer true in case, when, one relaxes the strict universality of the $\delta$-mSUGRA and considers simple extensions like non-universal Higgs mass models.

Before proceeding to $\delta$-NUHM, a couple of observations are important. Firstly, apart from the cancellation regions, the present limits on $\text{BR}(\tau \rightarrow \mu + \gamma)$ constraint $|\delta| \lesssim$
0.11 – 0.12 for tanβ of 20 and slepton mass of around 200 GeV ($M_{\tilde{\tau}} \sim 500$ GeV) in the co-annihilation regions. Since such values of δ are allowed by the data, one can consider them to be present in δ-mSUGRA. A larger value of δ would be valid for larger slepton masses. As discussed, this would lead to shifts in the parameter space of the co-annihilation region corresponding to mSUGRA. As a result, there is a shift in the spectrum also compared to mSUGRA. The thermally averaged cross-section are also modified. The shifts would be largest in the absence of any constraint from lepton flavor violation. For this reason, we look for overlapping regions between the cancellation and co-annihilation regions. Secondly, the cancellation region lies within a small narrow band. To the left and right of this band there could be regions of partial cancellations. These are present in figures 5. A discussion connected with this issue is present in appendix B.

3 Flavored co-annihilation in δ-NUHM

As we have seen in the previous section, in δ-mSUGRA, the μ parameter gets tied up with the neutralino mass in the co-annihilation region, thus leaving little room for cancellations within the flavor violating amplitudes. In the NUHM models, which are characterized by non-universal soft masses for the Higgs alone [39], the μ remains no longer restricted. This can be demonstrated with approximate formulae presented in appendix A.2. We denote the high scale mass parameters as $m_{H_u}^2(M_{GUT}) \equiv m_{20}^2$ and $m_{H_d}^2(M_{GUT}) \equiv m_{10}^2$. For $\tan \beta = 20$, using the approximate expressions in the appendix A.2, we see that $|\mu|^2$ has the form:

$$|\mu|^2 \approx 0.67 \, m_0^2 + 2.87 \, M_1^2 - 0.027 \, m_{10}^2 - 0.64 \, m_{20}^2$$ (3.1)

Setting $m_0^2 \approx m_{\tilde{\tau}_R}^2 - 0.15 M_{\tilde{\tau}}^2$ and $M_1 \approx 0.411 M_{\tilde{\tau}}$ and taking the limit $m_{\tilde{\tau}_R} \rightarrow M_1$ in the co-annihilation region, we have

$$|\mu|^2 \approx 17 \, M_1^2 - 0.027 \, m_{10}^2 - 0.64 \, m_{20}^2$$ (3.2)

thus providing enough freedom in terms of $m_{10}$ and $m_{20}$ to allow cancellations in the LFV amplitudes to co-exist with co-annihilation regions.

The dark matter phenomenology of NUHM models has been studied by several authors [39–44]. The LSP is a neutralino in large regions of the parameter space and further, it can admit large Higgsino fractions in its composition unlike in mSUGRA. For simplicity, we concentrate on Bino dominated regions in the following. In such a case the lightest neutralino mass, in terms of SUSY parameters is as in mSUGRA:

$$m_{\chi_1^0} \approx 0.411 M_{\tilde{\tau}}$$ (3.3)

For the lightest slepton mass one can use eq. (2.4) where now $m_{\tilde{\tau}_R}^2$ at weak scale will be determined by the NUHM boundary conditions at the GUT scale. Similar to the mSUGRA case, approximate solutions can be derived for the NUHM case also and they are presented in appendix A.2. Using the co-annihilation condition $m_{\tilde{l}_1} \approx m_{\chi_1^0}$ and the

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9$|\mu|^2 \approx 20.5 M_1^2$ in this limit in mSUGRA as can be seen from the expression below eq. (2.9).
Figure 6. Panels (from top-right in clockwise direction) depict $m_0$-$M_2$ plane with $m_{10} = m_{h\hat{d}} = 0.5 \cdot m_0$ and $m_{20} = m_{h\hat{u}} = 1.5 \cdot m_0$ for $\tan \beta = 20$, $A_0 = 0$ and $\text{sign}(\mu) > 0$, with $\delta = 0.2, 0.4, 0.6, 0.7$ respectively. Dark green region indicates inefficient REWSB. Purple region indicates $\tilde{l}_1$ LSP. Black shade marks the region excluded by unsuccessful search by LEP, $m_h < 114.5$ GeV. The violet dots represent the present limits form LHC [38]. The red dot-dashed line indicates 1 TeV contour for gluino and blue dotted line marks the 1 TeV contours for first two generation squark mass. Blue strip bordering $\tilde{l}_1$ LSP is the co-annihilation region. The different contour marks $\text{BR}(\tau \to \mu \gamma)$. The regions where the contours of $\text{BR}(\tau \to \mu \gamma) \lesssim 10^{-10}$ and below are the places where cancellations happen, which can be identified by their ‘band’ like structure.

cancellation condition $m_{\tau R}^2 \approx \mu^2$, one can derive expressions for $m_{10}^2$ and $m_{20}^2$ where flavored co-annihilations are of maximal importance.

The derived expressions for $m_{10}^2, m_{20}^2$ are however, complicated. We found simpler parameterizations for regions where the LSP is Bino dominated and co-annihilations with the $\tilde{l}_1$ are important. Examples of such regions are (i) $m_{20} = 1.5 \cdot m_0$ and $m_{10} = 0.5 \cdot m_0$ and (ii) $m_{20} = 3 \cdot m_0$ and $m_{10} = m_0$. For these values of $m_{10}$ and $m_{20}$, flavored co-annihilations can exist for non-zero $\delta$. In figure 6, we present in $m_0$, $M_1$ plane regions consistent with all constraints for $\delta = 0.2, 0.4, 0.6$ and 0.7, in an analogous fashion as to those presented in $\delta$-mSUGRA section, figure 5. We have chosen $m_{20} = 1.5 \cdot m_0$ and $m_{10} = 0.5 \cdot m_0$ for this plots. The purple region is excluded as the LSP is charged, here $m_{\tilde{l}_1} < m_{\chi_1^0}$. Dark green region indicates no radiative electroweak symmetry breaking, $|\mu|^2 < 0$. The translucent black
shaded region is excluded by search for light neutral higgs boson at LEP, $m_h < 114.5$ GeV. As in $\delta$-mSUGRA, we see that with increase in $\delta_{23}^{BR}$, $\tilde{l}_1 - \text{LSP}$ region increases owing to the reduction of mass of $\tilde{l}_1$. The impact of non-universality in the Higgs sector is negligible for $m_{\tilde{l}_1}$ in these regions. Analogously, regions excluded by light higgs search ($m_h < 114.5$ GeV) are weakly affected in the presence of $\delta$. Moreover, region with $|\mu|^2 < 0$ is not affected by $\delta$ as it is entirely governed by $m_0, m_{10}$ and $m_{20}$ with maximum contribution from $m_{20}$ and $m_0$. However, as expected the magnitude of $\text{BR}(\tau \rightarrow \mu \gamma)$ governed by eq. $(2.9)$, increases with $\delta_{23}^{RR}$. The last panel of the figure shows regions where cancellation regions overlaps with the co-annihilation regions for $\delta = 0.7$. For a different set of values of $m_{10}$ and $m_{20}$, for example, $m_{20} = 3 \cdot m_0, m_{10} = m_0$ the overlap regions can be found for even smaller values of $\delta$. In these regions flavored co-annihilations play a dominant role.

4 Channels

The individual scattering processes involved in the computation of thermally averaged cross-section are called channels. The typical channels which are dominant in the co-annihilation region are $\tilde{l}_1 \tilde{l}_1 \rightarrow l \bar{l}, \tilde{\chi}_1^0 \tilde{l}_1 \rightarrow \gamma l, \tilde{\chi}_1^0 \tilde{l}_1 \rightarrow Z l, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow l \bar{l}, \tilde{l}_1 \tilde{l}_1 \rightarrow l \bar{l}$ etc. (they are about thirty of them in total). In the presence of flavor violation the number of these processes would be enlarged to include flavor violating final states. In the present section, we analyze the relative importance of the new flavor violating channels with the corresponding flavor conserving ones as a function of $\delta$. To do this we fix $M_{1/2}$ and vary $\delta$ and $m_0$. In effect, this corresponds to the combination of horizontal sections of the co-annihilation regions of all the panels in figure 5 (figure 6) for $\delta$-mSUGRA ($\delta$-NUHM). In figure 7 we plot the dominant channels as a function of $\delta$ in $\delta$-mSUGRA. All the points satisfy relic density within WMAP 3$\sigma$ bound and lie in the co-annihilation region. Rest of the phenomenological constraints are also imposed. $m_0$ is varied from 100 to 600 GeV, whereas $M_{1/2}$ is fixed at 500 GeV, $\tan \beta = 20$ and $\text{sign}(\mu) > 0$. The Y-axis is percentage contribution to the thermally averaged cross section, $\langle \sigma v \rangle$ defined by

$$\% \langle \sigma v \rangle_{ij \rightarrow mn} = \frac{\langle \sigma v \rangle_{ij \rightarrow mn}}{\langle \sigma v \rangle_{\text{total}}} \times 100$$ (4.1)

It should be noted that flavor violating constraints are not imposed for $\delta$-mSUGRA in this analysis. The current limits on $\text{BR}(\tau \rightarrow \mu + \gamma)$ constraint $|\delta| \lesssim 0.11$ in the parameter space presented in the figure. For those values of $\delta$ we see that the flavor violating channels contribute up to 5% of the dominant channel contribution. Larger values of $\delta$ are not allowed after the imposition of this constraint as there is no overlap between cancellation regions and co-annihilation regions in $\delta$-mSUGRA. However, to study the features of the channels with respect to $\delta$ it would be useful not to impose the $\text{BR}(\tau \rightarrow \mu + \gamma)$ constraint for the present.

The upper left panel shows the $\% \langle \sigma v \rangle$ for $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow l \bar{l}$, which contributes about $\lesssim 5\%$ total to $\langle \sigma v \rangle$ in this region of parameter space. In this case, the initial state masses are independent of $\delta$ and $m_0$, and thus, the only variation comes from the mass of intermediate
Figure 7. Channels in δ-mSUGRA. The colored dots show relative contribution of a particular channel to $\langle \sigma v \rangle_{\text{tot}}$. $M_{1/2} = 500$ GeV and $m_0$ and $\delta$ are varied to fit the co-annihilation condition. Here all the points satisfy WMAP 3σ bound ($2.8$). For the above plots $\tan \beta$ is fixed to 20 and $\text{sign}(\mu) > 0$. Flavor violating constraints are not imposed here.

state particle ($\tilde{l}_1$). In table 3, we presented the sample points which are represented in the plot. From the points, I and II of table 3, we see that a slight shift of 5 GeV in $m_0$ is still allowed by WMAP 3σ limits, which changes the $\tilde{\chi}_0^0 \tilde{\chi}_1^1$ cross-section by about 40%. This is the reason why the band of allowed points is broad in this channel. Other dominant channels are represented in subsequent panels of the figure. From the panel it is obvious
that the dominant contribution comes from $\tilde{\tau}_1 \tilde{\nu}_1 \rightarrow \gamma \tau$ and $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \tau \tau$ channels. Each of which contribute to about 35% and 25% respectively to $\langle \sigma v \rangle$. Most of the flavor violating counterparts of these channels behave as expected, i.e. at large $\delta$, they become comparable to the flavor conserving ones. One exception of this is the $\tilde{\nu}_1 \tilde{\nu}_1$ channel. Here the initial state composition crucially depends on $'\delta'$ and also on $\tilde{\tau}_L \tilde{\tau}_R$ mixing. In such a situation, it is clear that the initial state cannot be attributed any flavor quantum number. In fact we find that the $\tilde{\mu}$ (smuon) component of $\tilde{\nu}_1$ can be large $\sim 50\%$ even for $\delta \approx 0.2$ in some regions of parameter space. We see from the figure that the flavor violating final states dominates over the flavor conserving ones, as $\delta$ grows beyond $\delta \gtrsim 0.2$. The exact point of crossing of the flavor violating channels over flavor conserving ones is dependent on the parameter space chosen, crucially on $\tan \beta$ and $\mu$. This is because the effective $\tilde{\mu}_L \tilde{\tau}_R$ and/or $\tilde{\mu}_R \tilde{\tau}_L$ coupling generated play an important role in determining the initial state composition. The last two panels shows some of the channels, which contribute negligibly to the $\langle \sigma v \rangle$. In appendix E we have given approximate formulae in $m_\tau/m_\mu \rightarrow 0$ limit for the dominant cross-sections. Using these and approximate formulae presented in appendix A features of full numerical analysis can be verified. More detailed analysis of cross-sections in the presence of flavor violation is various dark matter allowed regions will be presented elsewhere [45].

In figure 8, we present similar plots form channels in $\delta$-NUHM case for the parametrization chosen in the previous section. Here we have imposed $\text{BR}(\tau \rightarrow \mu \gamma) \leq 4.4 \times 10^{-8}$ to

| Parameters | Point I | Point II | Point III |
|------------|---------|----------|-----------|
| $M_1 = 500.0 \text{ GeV},$ | $M_1 = 500.0 \text{ GeV},$ | $M_1 = 500.0 \text{ GeV},$ |
| $\tan \beta = 20,$ | $\tan \beta = 20,$ | $\tan \beta = 20,$ |
| $m_0 = 165.6 \text{ GeV}$ | $m_0 = 169.6 \text{ GeV}$ | $m_0 = 249.0 \text{ GeV}$ |
| $\delta$ | 0.197 | 0.202 | 0.5 |
| $\Omega h^2$ | 0.0910 | 0.119 | 0.120 |
| $\chi^0_1 \tilde{\nu}_1 \rightarrow \gamma \tau$ | 0.206 | 0.227 | 0.181 |
| $\chi^0_1 \tilde{\nu}_1 \rightarrow \gamma \mu$ | $6.53 \times 10^{-2}$ | $7.47 \times 10^{-2}$ | 0.13 |
| $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \tau \tau$ | 0.211 | 0.181 | 0.116 |
| $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \tau \mu$ | 0.130 | 0.117 | 0.165 |
| $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \mu \mu$ | $2.10 \times 10^{-2}$ | $1.97 \times 10^{-2}$ | $5.97 \times 10^{-2}$ |
| $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow \gamma \gamma$ | 0.110 | 0.965 | $9.93 \times 10^{-2}$ |
| $\chi^0_1 \tilde{\nu}_1 \rightarrow Z \tau$ | $5.67 \times 10^{-2}$ | $6.23 \times 10^{-2}$ | $4.96 \times 10^{-2}$ |
| $\chi^0_1 \tilde{\nu}_1 \rightarrow Z \mu$ | $1.76 \times 10^{-2}$ | $2.02 \times 10^{-2}$ | $3.53 \times 10^{-2}$ |
| $\tilde{\nu}_1 \tilde{\nu}_1 \rightarrow Z \gamma$ | $5.00 \times 10^{-2}$ | $4.42 \times 10^{-2}$ | $5.18 \times 10^{-2}$ |
| $\chi^0_1 \chi^0_1 \rightarrow \tau \tilde{\tau}$ | $2.07 \times 10^{-2}$ | $2.81 \times 10^{-2}$ | $2.27 \times 10^{-2}$ |
| $\chi^0_1 \chi^0_1 \rightarrow \tau \tilde{\mu}$ | $6.76 \times 10^{-3}$ | $9.50 \times 10^{-3}$ | $8.29 \times 10^{-3}$ |
| $\chi^0_1 \chi^0_1 \rightarrow \mu \tilde{\mu}$ | $1.73 \times 10^{-2}$ | $2.42 \times 10^{-2}$ | $1.80 \times 10^{-2}$ |

Table 3. $\frac{\langle \sigma v \rangle_{\text{channel}}}{\langle \sigma v \rangle_{\text{total}}}$ for dominant channels for $\delta$-mSUGRA.
be satisfied along with relic density constraints. These channel show a similar pattern here as in \( \delta \)-mSUGRA. However, as we can see from the panels, there is a gap between \( \delta = 0.2 \) to \( \delta = 0.7 \) where the parameter space does not satisfy \( \text{BR}(\tau \to \mu \gamma) \leq 4.4 \times 10^{-8} \). For points below \( \delta \leq 0.2 \), this constraint is satisfied as \( \delta \) is too small to generate appreciable \( \tau \to \mu + \gamma \) amplitudes. For \( \delta \geq 0.7 \), the constraint is now satisfied because of the overlap between the cancellation regions and co-annihilation regions. The relative contribution in the overlap region is magnified in figure 9 where all the channels contributions are presented between \( 0.70 \leq \delta \leq 0.85 \). As we can see, flavor violating channels strongly compete with flavor conserving ones. A sample of the points in \( \delta \)-NUHM is presented in table 4, where points IV and V represent low \( \delta \) values whereas point VI represent the large \( \delta \) value signifying overlapping regions.

Finally a note about relative contribution to relic density. We have

\[
\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle_{\text{total}}} = \frac{1}{\sum_{\text{all channels}} \langle \sigma v \rangle_i} \\
\phantom{\Omega h^2} \propto \frac{1}{\langle \sigma v \rangle_{\text{total}}} \sum_{\text{all channels}} \frac{\langle \sigma v \rangle_i}{\langle \sigma v \rangle_{\text{total}}}
\]

(4.2)

For small \( \delta \left( \sim \mathcal{O}(10^{-2}) \right) \) where \( \langle \sigma v \rangle \) contribution to flavor violating channel is small, the

| Parameters | Point IV | Point V | Point VI |
|-----------|---------|---------|---------|
| \( M_\chi \) = 750.0 GeV, \( \tan \beta = 20 \), \( m_0 = 199.3 \) GeV | \( M_\chi \) = 750.0 GeV, \( \tan \beta = 20 \), \( m_0 = 216.0 \) GeV | \( M_\chi \) = 750.0 GeV, \( \tan \beta = 20 \), \( m_0 = 592.1 \) GeV |
| \( \delta \) | 0.01 | 0.12 | 0.767 |
| \( \Omega h^2 \) | 0.115 | 0.116 | 0.111 |
| \( \overline{\chi}_1 \overline{l}_1 \to \gamma \tau \) | 0.190 | 0.168 | 0.116 |
| \( \chi_1^0 \overline{l}_1 \to \gamma \mu \) | 4.74 \times 10^{-4} | 3.89 \times 10^{-2} | 9.89 \times 10^{-2} |
| \( \overline{l}_1 l_1 \to \tau \tau \) | 0.388 | 0.280 | 0.134 |
| \( \overline{l}_1 l_1 \to \mu \mu \) | 1.90 \times 10^{-3} | 0.127 | 0.227 |
| \( l_1 l_1 \to \mu \mu \) | 2.39 \times 10^{-6} | 1.48 \times 10^{-2} | 9.37 \times 10^{-2} |
| \( \overline{l}_1 l_1 \to \gamma \gamma \) | 0.115 | 0.123 | 0.129 |
| \( l_1 l_1 \to \gamma \gamma \) | 5.50 \times 10^{-2} | 4.88 \times 10^{-2} | 3.35 \times 10^{-2} |
| \( \chi_1^0 l_1 \to Z \tau \) | 2.02 \times 10^{-6} | 1.11 \times 10^{-2} | 2.28 \times 10^{-2} |
| \( \chi_1^0 l_1 \to Z \gamma \) | 5.67 \times 10^{-2} | 6.36 \times 10^{-2} | 7.49 \times 10^{-2} |
| \( \chi_1^0 l_1 \to \tau \bar{\tau} \) | 1.14 \times 10^{-2} | 1.13 \times 10^{-2} | 3.72 \times 10^{-3} |
| \( \alpha \chi_1^0 \to \tau \bar{\mu} \) | 2.80 \times 10^{-5} | 1.77 \times 10^{-3} | 3.53 \times 10^{-3} |
| \( \chi_1^0 \chi_1^0 \to \mu \bar{\mu} \) | 9.53 \times 10^{-3} | 9.87 \times 10^{-3} | 4.49 \times 10^{-3} |

Table 4. \( \langle \sigma v \rangle_{\text{channel}} \) for dominant channels for \( \delta \)-NUHM.
Figure 8. Channels in $\delta$-NUHM. The colored dots show relative contribution of a particular channel to $\langle \sigma v \rangle_{\text{tot}}$. $M_{1/2} = 750$ GeV and $m_0$ and $\delta$ are varied to fit the co-annihilation condition. Here all the points satisfy WMAP $3\sigma$ bound (2.8). For the above plots $\tan \beta$ is fixed to 20 and sign$(\mu) > 0$. Flavor violating constraints are imposed here, which causes the discontinuous regions in each of the channels.

estimate of relic density does not modify much from the flavor conserving case. However for large enough $\delta \left(\sim \mathcal{O}(10^{-1})\right)$, one tends to overestimate relic density, if one does not consider flavor violating scatterings while computing the thermally averaged cross-section.
Figure 9. Dominant channels contribution to the $\langle \sigma v \rangle_{\text{tot}}$. Here $\tan \beta$ is fixed to 20, $M_{1/2} = 750$ GeV and $m_0$ and $\delta$ are varied to fit the co-annihilation condition. Here all the points satisfy WMAP 3σ bound (2.8).

5 Summary and outlook

We have generalized the co-annihilation process by including flavor violation in the sleptonic $\mu - \tau$ (RR) sector. The amount of flavor violation admissible is constrained to be small by the limit on the BR($\tau \rightarrow \mu + \gamma$). This constraint is significantly weakened in regions of the parameter space where cancellations in the amplitudes takes place. We look for regions of parameter space where there is a significant overlap between cancellation regions and co-annihilation regions. The search is done in mSUGRA and NUHM augmented with one single flavor violating parameter in the $\mu - \tau$ (RR) sector. We found that while no significant overlap is possible in $\delta$-mSUGRA, $\delta$-NUHM allows for large regions where significant overlap is possible.

The presence of flavor violation shifts the lightest slepton co-annihilation regions towards lighter neutralino masses compared to mSUGRA. While computing the thermally averaged cross-sections in the overlap regions, we found that flavor violating processes could contribute with equal strength and in some cases even dominantly compared to the flavor conserving ones. This is true even for $\delta \gtrsim 0.2$ in some regions of the parameter space. Neglecting the flavor violating channels would lead to underestimating the cross section and thus in overestimating the relic density. A point to note is that if flavor violation is present even within the presently allowed limits, it could still change the dominant chan-
nels by about 5% in δ-mSUGRA and more in δ-NUHM. Finally, We have probed only a minor region of the parameter space in the present work demonstrating the existence of such regions. A comprehensive analysis of such regions and the associated phenomenology of their spectrum would be interesting in their own right.

In this respect, a few comments on flavor violation at the LHC and ILC are in order. Detection of lepton flavor violation at the colliders like LHC is strongly constrained by experimental limits on rare lepton flavor violating decays. One standard technique to detect flavor violation at colliders is to study the slepton mass differences using end-point kinematics of cascade decays [46]. The typical sensitivity being discussed in the literature is \[ \frac{\Delta m_{\tilde{l}_i}}{m_{\tilde{l}_i}} \approx O(0.1)\% \text{ for } \tilde{e}_L - \tilde{\mu}_L \text{ and } O(1)\% \text{ for } \tilde{\mu}_L - \tilde{\tau}_L [47]. \] In the presence of \[ \Delta_{RR}^{\mu\tau} \] splittings are generated in all the three eigenvalues [48], e - \mu, \mu - \tau, e - \tau sectors. In the case discussed in this work, the typical splittings are \[ O(20)\% \text{ to } O(70)\% \] as the constraints from LFV experiments are evaded. Thus, far less sensitivity is required to measure these splittings compared to the regular case. Further investigations in this direction are however needed. Another interesting aspect of this scenario would be to measure widths for LFV decay processes like \[ \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \tilde{\tau}. \] These widths have been studied for the case of right handed slepton flavor violation in [49]. In NUHM, with a comparatively smaller value of \[ \mu \] one could expect large production cross sections for \[ \tilde{\chi}^0_4 \text{ and } \tilde{\chi}^\pm_2 \] in the decays of colored particles. In fact, a full Monte Carlo study has been reported by Hisano et al. [33] for a particular parameter space point in the model.

At the linear collider, it should be possible to identify the \( \tilde{\tau} \) co-annihilation region [50–54] by studying the polarization of the decay \( \tilde{\tau}_1 \rightarrow \tilde{\chi}^0_1 \tau \). In the presence of flavored co-annihilations one should be able to see flavor violating decays of \( \tilde{\tau}_1 \). Heavier particles like \( \tilde{\tau}_2 \) and charginos would also have flavor violating decays.

Finally let’s note that we have considered the cancellations in the dipole operator of the \( \tau \rightarrow \mu \) transitions, it does not guarantee us suppression in amplitudes associated with other operators. For example, in this region \( \tau \rightarrow \mu \eta \) or \( \tau \rightarrow \mu \eta' \) could be sizable (\( \sim 10^{-9} - 10^{-10} \)) [55], which could be probed in future B-factories. Whereas, \( \tau \rightarrow \mu \gamma \) will continue to remain constrained and thus will not be detected.

The focus of the present work has been to introduce new regions of parameter space where flavor effects in the co-annihilation regions could be important. More generally flavor effects could play a role in any dark matter ‘regions’ of the SUSY parameter space. Such studies are being explored in [45].

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A Approximate solutions

A.1 mSUGRA case

In the approximation of small Yukawa couplings, we retain only $Y_t$, $Y_b$, $Y_\tau$ and solve the RGEs semi-analytically. For the first two generations of the particles the dependence on $\tan \beta$ is very weak, so we take them to be valid for all $\tan \beta$. In deriving the approximate expressions we have taken $m_t(M_Z) = 165$ GeV, $m_b(M_Z) = 3$ GeV and $m_\tau(M_Z) = 1.77$ GeV.

For $\tan \beta = 5$, the first two generation masses at the weak scale are

\[(m_{Q_1,2}^2(M_Z)) \simeq m_0^2 + 6.66 M_Z^2/3 \] (A.1)
\[(m_{D_1,2}^2(M_Z)) \simeq m_0^2 + 6.19 M_Z^2/2 \] (A.2)
\[(m_{U_1,2}^2(M_Z)) \simeq m_0^2 + 6.22 M_Z^2/2 \] (A.3)
\[(m_{L_1,2}^2(M_Z)) \simeq m_0^2 + 0.51 M_Z^2/2 \] (A.4)
\[(m_{E_1,2}^2(M_Z)) \simeq m_0^2 + 0.17 M_Z^2/2 \] (A.5)

Third generation masses strongly depend on $\tan \beta$ than the first two generations. For low $\tan \beta = 5$ their values are as follows

\[(m_{Q_3}^2(M_Z)) \simeq -0.036 A_0^2 + 0.65 m_0^2 + 0.16 A_0 M_Z^2 + 5.66 M_Z^2 \] (A.6)
\[(m_{U_3}^2(M_Z)) \simeq -0.070 A_0^2 + 0.31 m_0^2 + 0.30 A_0 M_Z^2 + 4.26 M_Z^2 \] (A.7)
\[(m_{D_3}^2(M_Z)) \simeq -1.70 \times 10^{-3} A_0^2 + m_0^2 + 7.23 \times 10^{-3} A_0 M_Z^2 + 6.17 M_Z^2 \] (A.8)
\[(m_{L_3}^2(M_Z)) \simeq -7.34 \times 10^{-4} A_0^2 + m_0^2 + 6.29 \times 10^{-4} A_0 M_Z^2 + 0.51 M_Z^2 \] (A.9)
\[(m_{E_3}^2(M_Z)) \simeq -1.47 \times 10^{-3} A_0^2 + m_0^2 + 1.26 \times 10^{-3} A_0 M_Z^2 + 0.16 M_Z^2 \] (A.10)
\[m_{H_u}^2(M_Z) \simeq -3.30 \times 10^{-3} A_0^2 + 0.99 m_0^2 + 0.01 A_0 M_Z^2 + 0.48 M_Z^2 \] (A.11)
\[m_{H_d}^2(M_Z) \simeq -0.105 A_0^2 - 0.046 m_0^2 + 0.46 A_0 M_Z^2 - 2.95 M_Z^2 \] (A.12)
\[|\mu|^2(M_Z) = -4158.72 + 0.110 A_0^2 + 0.084 m_0^2 - 0.47 A_0 M_Z^2 + 3.09 M_Z^2 \] (A.13)

For medium $\tan \beta = 20$ their values are as follows

\[(m_{Q_3}^2(M_Z)) \simeq -0.048 A_0^2 + 0.62 m_0^2 + 0.20 A_0 M_Z^2 + 5.54 M_Z^2 \] (A.14)
\[(m_{U_3}^2(M_Z)) \simeq -0.070 A_0^2 + 0.33 m_0^2 + 0.30 A_0 M_Z^2 + 4.32 M_Z^2 \] (A.15)
\[(m_{D_3}^2(M_Z)) \simeq -0.023 A_0^2 + 0.91 m_0^2 + 0.10 A_0 M_Z^2 + 5.86 M_Z^2 \] (A.16)
\[(m_{L_3}^2(M_Z)) \simeq -0.011 A_0^2 + 0.97 m_0^2 + 8.38 \times 10^{-3} A_0 M_Z^2 + 0.50 M_Z^2 \] (A.17)
\[(m_{E_3}^2(M_Z)) \simeq -0.021 A_0^2 + 0.93 m_0^2 + 0.017 A_0 M_Z^2 + 0.15 M_Z^2 \] (A.18)
\[m_{H_u}^2(M_Z) \simeq -0.046 A_0^2 + 0.83 m_0^2 + 0.16 A_0 M_Z^2 + 0.01 M_Z^2 \] (A.19)
\[m_{H_d}^2(M_Z) \simeq -0.105 A_0^2 - 0.007 m_0^2 + 0.46 A_0 M_Z^2 - 2.86 M_Z^2 \] (A.20)
\[|\mu|^2(M_Z) = -4158.72 + 0.106 A_0^2 + 0.009 m_0^2 - 0.46 A_0 M_Z^2 + 2.87 M_Z^2 \] (A.21)
For high $\tan \beta = 35$ their values are as follows

\[
\begin{align*}
(m_Q^2)_{13}(M_Z) &\simeq -0.058 A_0^2 + 0.53 m_0^2 + 0.25 A_0 M_1 + 5.26 M_t^2 & (A.22) \\
(m_U^2)_{13}(M_Z) &\simeq -0.064 A_0^2 + 0.33 m_0^2 + 0.27 A_0 M_1 + 4.35 M_t^2 & (A.23) \\
(m_D^2)_{13}(M_Z) &\simeq -0.052 A_0^2 + 0.727 m_0^2 + 0.23 A_0 M_1 + 5.26 M_t^2 & (A.24) \\
(m_D^2)_{12}(M_Z) &\simeq -0.027 A_0^2 + 0.89 m_0^2 + 0.02 A_0 M_1 + 0.49 M_t^2 & (A.25) \\
(m_U^2)_{12}(M_Z) &\simeq -0.055 A_0^2 + 0.78 m_0^2 + 0.03 A_0 M_1 + 0.12 M_t^2 & (A.26) \\
m_H^2(M_Z) &\simeq -0.105 A_0^2 + 0.48 m_0^2 + 0.36 A_0 M_1 - 0.91 M_t^2 & (A.27) \\
m_H^2(M_Z) &\simeq -0.095 A_0^2 - 0.005 m_0^2 + 0.41 A_0 M_1 - 2.81 M_t^2 & (A.28) \\
|M|^2(M_Z) &\simeq - 4158.72 + 0.095 A_0^2 + 0.005 m_0^2 - 0.41 A_0 M_1 + 2.81 M_t^2 & (A.29)
\end{align*}
\]

### A.2 NUHM case

In our notation $m_{10} = m_{H_d}(M_{GUT})$ and $m_{20} = m_{H_u}(M_{GUT})$. For $\tan \beta = 5$, at the weak scale the first two generation masses are

\[
\begin{align*}
(m_Q^2)_{12}(M_Z) &\simeq m_0^2 + 6.66 M_t^2 + 0.009 (m_{10} - m_{20}) & (A.30) \\
(m_D^2)_{12}(M_Z) &\simeq m_0^2 + 6.19 M_t^2 + 0.018 (m_{10} - m_{20}) & (A.31) \\
(m_U^2)_{12}(M_Z) &\simeq m_0^2 + 6.22 M_t^2 - 0.036 (m_{10} - m_{20}) & (A.32) \\
(m_L^2)_{12}(M_Z) &\simeq m_0^2 + 0.51 M_t^2 - 0.027 (m_{10} - m_{20}) & (A.33) \\
(m_E^2)_{12}(M_Z) &\simeq m_0^2 + 0.17 M_t^2 + 0.053 (m_{10} - m_{20}) & (A.34)
\end{align*}
\]

Third generation masses strongly depend on $\tan \beta$ than the first two generations. For low $\tan \beta = 5$ their values are as follows

\[
\begin{align*}
(m_Q^2)_{3}(M_Z) &\simeq -0.036 A_0^2 + 0.77 m_0^2 + 0.16 A_0 M_1 + 5.66 M_t^2 + 7.90 \times 10^{-3} m_{10} \\
&- 0.125 m_{20} & (A.35) \\
(m_U^2)_{3}(M_Z) &\simeq -0.070 A_0^2 + 0.54 m_0^2 + 0.30 A_0 M_1 + 4.26 M_t^2 - 0.035 m_{10} \\
&- 0.196 m_{20} & (A.36) \\
(m_D^2)_{3}(M_Z) &\simeq -1.70 \times 10^{-3} A_0^2 + m_0^2 + 7.23 \times 10^{-3} A_0 M_1 + 6.17 M_t^2 + 0.016 m_{10} \\
&- 0.018 m_{20} & (A.37) \\
(m_L^2)_{3}(M_Z) &\simeq -7.34 \times 10^{-4} A_0^2 + m_0^2 + 6.29 \times 10^{-4} A_0 M_1 + 0.51 M_t^2 - 0.027 m_{10} \\
&+ 0.027 m_{20} & (A.38) \\
(m_E^2)_{3}(M_Z) &\simeq -1.47 \times 10^{-3} A_0^2 + m_0^2 + 1.26 \times 10^{-3} A_0 M_1 + 0.16 M_t^2 + 0.052 m_{10} \\
&- 0.053 m_{20} & (A.39)
\end{align*}
\]
\[ m_{H_u}^2(M_Z) \simeq -3.30 \times 10^{-3} A_0^2 - 7.32 \times 10^{-3} m_0^2 + 0.01 A_0 M_2 + 0.48 M_2^2 + 0.969 m_{10}^2 + 0.027 m_{20}^2 \] 
\[ m_{H_d}^2(M_Z) \simeq -0.105 A_0^2 - 0.70 m_0^2 + 0.46 A_0 M_1 - 2.95 M_2^2 + 0.027 m_{10}^2 + 0.625 m_{20}^2 \] 
\[ |\mu|^2(M_Z) = -4158.72 + 0.110 A_0^2 + 0.72 m_0^2 - 0.47 A_0 M_2 + 3.09 M_2^2 + 0.012 m_{10}^2 - 0.650 m_{20}^2 \]

For medium \( \tan \beta = 20 \) their values are as follows
\[ (m_Q^2)_3(M_Z) \simeq -0.048 A_0^2 + 0.75 m_0^2 + 0.20 A_0 M_2 + 5.54 M_2^2 - 6.30 \times 10^{-3} m_{10}^2 - 0.120 m_{20}^2 \] 
\[ (m_U^2)_3(M_Z) \simeq -0.070 A_0^2 + 0.55 m_0^2 + 0.30 A_0 M_2 + 4.32 M_2^2 - 0.034 m_{10}^2 - 0.190 m_{20}^2 \] 
\[ (m_D^2)_3(M_Z) \simeq -0.023 A_0^2 + 0.94 m_0^2 + 0.10 A_0 M_2 + 5.86 M_2^2 - 0.015 m_{10}^2 - 0.015 m_{20}^2 \] 
\[ (m_L^2)_3(M_Z) \simeq -0.011 A_0^2 + 0.98 m_0^2 + 8.38 \times 10^{-3} A_0 M_2 + 0.50 M_2^2 - 0.038 m_{10}^2 + 0.027 m_{20}^2 \] 
\[ (m_E^2)_3(M_Z) \simeq -0.021 A_0^2 + 0.95 m_0^2 + 0.017 A_0 M_2 + 0.15 M_2^2 + 0.030 m_{10}^2 - 0.053 m_{20}^2 \] 
\[ m_{H_u}^2(M_Z) \simeq -0.046 A_0^2 - 0.11 m_0^2 + 0.16 A_0 M_2 + 0.01 M_2^2 + 0.913 m_{10}^2 + 0.030 m_{20}^2 \] 
\[ m_{H_d}^2(M_Z) \simeq -0.105 A_0^2 - 0.67 m_0^2 + 0.46 A_0 M_2 - 2.86 M_2^2 + 0.030 m_{10}^2 + 0.634 m_{20}^2 \] 
\[ |\mu|^2(M_Z) = -4158.72 + 0.106 A_0^2 + 0.67 m_0^2 - 0.46 A_0 M_2 + 2.87 M_2^2 - 0.027 m_{10}^2 - 0.636 m_{20}^2 \]

For high \( \tan \beta = 35 \) their values are as follows
\[ (m_Q^2)_3(M_Z) \simeq -0.058 A_0^2 + 0.69 m_0^2 + 0.25 A_0 M_2 + 5.26 M_2^2 - 0.037 m_{10}^2 - 0.120 m_{20}^2 \] 
\[ (m_U^2)_3(M_Z) \simeq -0.064 A_0^2 + 0.55 m_0^2 + 0.27 A_0 M_2 + 4.35 M_2^2 - 0.029 m_{10}^2 - 0.194 m_{20}^2 \] 
\[ (m_D^2)_3(M_Z) \simeq -0.052 A_0^2 + 0.82 m_0^2 + 0.23 A_0 M_2 + 5.26 M_2^2 - 0.081 m_{10}^2 - 0.010 m_{20}^2 \] 
\[ (m_L^2)_3(M_Z) \simeq -0.027 A_0^2 + 0.93 m_0^2 + 0.02 A_0 M_2 + 0.49 M_2^2 - 0.063 m_{10}^2 + 0.027 m_{20}^2 \]
\[ (m_E^2)_{\delta}(M_Z) \simeq -0.055 A_0^2 + 0.85 m_0^2 + 0.03 A_0 M_{1/2} + 0.12 M_{1/2}^2 - 0.019 m_{10}^2 - 0.054 m_{20}^2 \]  
\[ m_{Hd}^2(M_Z) \simeq -0.105 A_0^2 - 0.35 m_0^2 + 0.36 A_0 M_{1/2} - 0.91 M_{1/2}^2 + 0.789 m_{10}^2 + 0.038 m_{20}^2 \]  
\[ m_{Hu}^2(M_Z) \simeq -0.095 A_0^2 - 0.67 m_0^2 + 0.41 A_0 M_{1/2} - 2.81 M_{1/2}^2 + 0.036 m_{10}^2 + 0.629 m_{20}^2 \]

\[ |\mu|^2(M_Z) = -4158.72 + 0.095 A_0^2 + 0.67 m_0^2 - 0.41 A_0 M_{1/2} + 2.81 M_{1/2}^2 - 0.036 m_{10}^2 - 0.629 m_{20}^2 \]

### B Lightest slepton mass in \( \delta \)-mSUGRA at large \( \delta \)

From the plots presented in section 2, figure 5, for the case of \( \delta \)-mSUGRA, the following two things can be inferred: (a) the co-annihilation condition increasingly moves towards the diagonal in \((m_0, M_{1/2})\) plane with increasing \( \delta \) and (b) the cancellation region are almost independent of the value of \( \delta \) in \((m_0, M_{1/2})\) plane. The question then arises if there is some region at large ‘\( \delta \)’ where the two regions coincide. In the present appendix, we explore this question. The analysis presented here is based on the approximate solutions of appendix A.1 and we will comment on the full numerical solutions at the end of the section.

The effective 4 \( \times \) 4 matrix of eq. (2.2) can be diagonalized as follows. First the lower 2 \( \times \) 2 block is rotated by an angle \( \theta \), given by,

\[ \tan 2\theta_{\mu\tau} = \frac{2 \Delta_{RR}}{m_{\tilde{\mu}R}^2 - m_{\tilde{\tau}R}^2}. \]  

(B.1)

The eigenvalues of this lower block can be easily read off from the mass matrix. They are

\[ \lambda^2_{\pm} = \frac{1}{2} \left[ (m_{\tilde{\mu}R}^2 + m_{\tilde{\tau}R}^2) \pm \sqrt{(m_{\tilde{\mu}R}^2 - m_{\tilde{\tau}R}^2)^2 + 4 \Delta_{RR}^2} \right] \]  

(B.2)

For \( m_{\tilde{\mu}R}^2 \simeq m_{\tilde{\tau}R}^2 \) (which is true for low tan \( \beta \) regions), the eigenvalues have the following form:

\[ \lambda^2_{\pm} \simeq \bar{m}^2 \pm \Delta_{RR} \]  

\[ \simeq \bar{m}^2(1 \pm \delta_{RR}) \]  

(B.3)

(B.4)

where \( \bar{m}^2 = \frac{1}{2} (m_{\tilde{\mu}R}^2 + m_{\tilde{\tau}R}^2) \). Next we have to diagonalize the \( \tilde{\tau}_{LR} \) entry. The eigenvalues after this rotation are approximately given as

\[ \Gamma^2_{\pm} \simeq \frac{1}{2} \left[ (m_{\tilde{\tau}L}^2 + \lambda^2) \pm \sqrt{(m_{\tilde{\tau}L}^2 - \lambda^2)^2 + 4 \cos^2 \theta_{\mu\tau} \Delta_{LR}^2} \right] \]  

(B.5)
In the limit \( (m^2_{\tilde{\tau}_L} - \lambda^2) \gg \Delta_{\tilde{\tau}_{LR}} \) (the corresponding angle is very small in this limit),\(^{10}\) which is the case for large \( \delta \), we can write the above eigenvalues as

\[
\Gamma^2_\pm \simeq \frac{1}{2} \left[ (m^2_{\tilde{\tau}_L} + \lambda^2) \pm (m^2_{\tilde{\tau}_L} - \lambda^2) \right] \left[ 1 + \frac{2 \cos^2 \theta_{\mu\tau} \Delta^2_{\tilde{\tau}_{LR}}}{(m^2_{\tilde{\tau}_L} - \lambda^2)^2} \right] \quad (B.6)
\]

So, the lightest eigenvalue of the effective 4 \( \times \) 4 mass matrix of eq. (2.2) is given as

\[
\begin{align*}
\Gamma^2_- &\simeq \lambda^2 - \frac{\cos^2 \theta_{\mu\tau} \Delta^2_{\tilde{\tau}_{LR}}}{m^2_{\tilde{\tau}_L} - \lambda^2} \\
&\simeq m^2(1 - \delta_{RR}) - \frac{\cos^2 \theta_{\mu\tau} \Delta^2_{\tilde{\tau}_{LR}}}{m^2_{\tilde{\tau}_L} - \bar{m}^2(1 - \delta_{RR})} \quad (B.7)
\end{align*}
\]

Which essentially suppresses the left-right mixing term compared to eq. (2.4). And demanding the lightest eigenvalue to be non-tachyonic we get an upper bound on \( \delta_{RR} \) as below

\[
\delta_{RR} \leq 1 - \frac{\cos^2 \theta_{\mu\tau} \Delta^2_{\tilde{\tau}_{LR}}}{m^2_{\tilde{\tau}_L} m^2_{\tilde{\tau}_R}} \quad (B.9)
\]

Which matches with eq. (2.5) in the limit \( \cos \theta_{\mu\tau} \to 1 \).

In figure 10 we have plotted the tachyonic condition (r.h.s. of eq. (B.9)) using the approximate results of appendix A. It has been plotted for two values of \( \tan \beta \) 20 and 35. The contours represent the upper bounds on \( \delta \) in those regions of the parameter space to avoid tachyonic leptons. As we can see, increasing \( \tan \beta \), tightens the bound a bit. In figure 11 we have shown the cancellation condition \( \mu^2 \simeq m^2_{\tilde{\tau}_R} \) and the co-annihilation condition \( m_{\tilde{l}_1} \simeq m_{\tilde{\chi}^0_1} \) for two values of \( \delta = 0.8 \) and 0.9. In both the panels, the brown and magenta solid lines indicate co-annihilation condition for \( \delta = 0.8 \) and 0.9 respectively. The green dashed line satisfy the cancellation condition, whereas the orange and red dashed lines satisfy the cancellation condition with the \( \mu \) parameter being 30% corrected than its tree level value. Comparing the figures 10 and 11 we can see that there could be some points which could evade both the tachyonic condition as well as have cancellations amongst the LFV amplitudes and still satisfy the co-annihilation condition. However in practice in full numerical calculation, we could not find any points consistent with both these conditions as other phenomenological constraints rule them out. As can be seen from the figure, a 30% correction to the \( \mu \) parameter could shift the overlapping region to very small values of \( (m_0, M_{1/2}) \) or no overlap at all for \( \delta \simeq 0.9 \). This approximates the implications of adding the full 1-loop effective corrections to the SUSY scalar potential. However, the co-annihilation region could allow for partial calculations in LFV amplitudes. Such regions are difficult to distinguish in a numerical analysis.

We will now return to eq. (B.5) and consider the limit \( (m^2_{\tilde{\tau}_L} - \lambda^2) \ll \Delta_{\tilde{\tau}_{LR}} \), which is an interesting limit as it is relevant for the regions which appear in channels plots discussed in section 4. From eq. (B.6), there could be a value of \( \delta \) as well as parameter space in \( (m_0, M_{1/2}, \tan \beta) \) where \( m^2_{\tilde{\tau}_L} \simeq \lambda^2 \). In these regions, the corresponding mixing angle is very large and the subsequent diagonalization is very different. It turns out that at least three mixing angles in the slepton mass matrix are large in this parameter space. The
Figure 10. $\delta$ contours: upper bounds on $\delta$ in various of the parameter space using the non-tachyonic condition.

Figure 11. Cancellation and co-annihilation region in $\delta$-mSUGRA.

plots presented in figures 7 and 8 contain these regions. More details of these regions will be discussed in [45].

C Numerical procedures

C.1 SuSeFLAV and MicrOMEGAs

The numerical analysis is done using publicly available package MicrOMEGAs [35] and SuSeFLAV [56]. SuSeFLAV is a fortran package which computes the supersymmetric spectrum by considering lepton flavor violation. The program solves complete MSSM RGEs with complete $3 \times 3$ flavor mixing at 2-loop level and full one loop threshold corrections [57]
to all MSSM parameters and relevant SM parameters, with conserved R-parity. Also, the program computes branching ratios and decay rates for rare flavor violating processes such as $\mu \rightarrow e \gamma, \tau \rightarrow e \gamma, \tau \rightarrow \mu \gamma, \mu \rightarrow e^+ e^- e^-, \tau^- \rightarrow \mu^+ \mu^- \mu^-, \tau^- \rightarrow e^+ e^- e^-, B \rightarrow s \gamma$ and $(g-2)_\mu$.

In the present analysis we use $M_t^{pole} = 173.2$ GeV, $M_b^{pole} = 4.23$ GeV and $M_\tau^{pole} = 1.77$ GeV. In determining the lightest higgs mass ($m_h$) we use approximations for one loop correction which are mostly top-stop enhanced \[58\]. We use complete $6 \times 6$ slepton mass matrix to correctly evaluate the inter-generational mixings and masses in the presence of flavor violation.

Moreover we consider flavor violating couplings stemming from lepton flavor violation in the RR sector of $\tilde{\tau} - \tilde{\mu}$.

- **Neutralino-slepton-lepton:**

  The interaction Lagrangian for neutralino-slepton-lepton is written as (figure 12 a)

  $$\mathcal{L} = \bar{l}_i (\Sigma^L_{iAX} P_L + \Sigma^R_{iAX} P_R) \chi^0_A \tilde{l}_X + h.c.$$  (C.1)

  Where the coefficients are defined as

  $$\Sigma^R_{iAX} = K_1 [\cos \theta_W (O_N)_{A2} + \sin \theta_W (O_N)_{A1}] U_{Xi} M_W \cos \beta$$

  $$- m_{l_i} \cos \theta_W (O_N)_{A3} U_{X,i+3}$$  (C.2)

  and

  $$\Sigma^L_{iAX} = -K_1 [2 \sin \theta_W M_W \cos \beta U_{X,i+3} (O_N)_{A1} + m_{l_i} \cos \theta_W U_{X,i} (O_N)_{A3}]$$  (C.3)

  where

  $$K_1 = \frac{e}{\sqrt{2} \sin \theta_W} \frac{1}{M_W \cos \beta \cos \theta_W}$$  (C.4)

- **Chargino-slepton-lepton:**

  The Interaction Lagrangian for chargino-slepton-neutrino is (figure 12 b)

  $$\mathcal{L} = \bar{\nu}_i (\Pi^L_{iBX} P_L + \Pi^R_{iBX} P_R) \chi^+_B \tilde{l}_X + h.c.$$  (C.5)

  Where the coefficients are

  $$\Pi^R_{iBX} = -\frac{e}{\sin \theta_W} (O_L)_{Bi} U_{Xi}$$  (C.6)

  $$\Pi^L_{iBX} = \frac{m_{l_i}}{\sin \theta_W \sqrt{2} M_W \cos \beta} (O_L)_{B2} U_{X,i+3}$$  (C.7)

  Where, $U_{X,i}$ is the $6 \times 6$ matrix which diagonalizes the sleptonic mass matrix, here the indices $i = 1$ to 3 and $X = 1$ to 6. $(O_N)_{Am}$ is the $4 \times 4$ neutralino mixing matrix, where $A, m = 1$ to 4 and $(O_L)_{Bn}$ is the $2 \times 2$ chargino left eigenvector matrix, where $B, n = 1, 2$. $m_{l_i}$ is the mass of the lepton $l_i$. In our notation $P_L = \frac{1-\gamma_5}{2}$ and $P_R = \frac{1+\gamma_5}{2}$.

  These couplings are programmed into MicrOMEGAs through CalcHEP \[59\] package.
C.2 Constraints imposed

- We check for efficient radiative electroweak symmetry breaking, requiring $|\mu|^2 > 0$ for valid points.
- We require $m_{\tilde{\tau}} > m_{\chi^0}$ as LSP is neutral. Regions for which this condition is not true is excluded as $\tilde{\tau}$ LSP regions.
- We impose lower bounds on various sparticle masses that results from collider experiments. $m_h > 114.1(\text{GeV})$, $m_{\chi^\pm} > 103.5(\text{GeV})$ and $m_{\tilde{\tau}} > 90(\text{GeV})$ [60].
- $2.0 \times 10^{-4} \leq BR(b \rightarrow s \gamma) \leq 4.5 \times 10^{-4}$ [37].
- We also check for the D-flat directions, while checking for the EWSB condition and charge and color breaking minima [61–63].

D Loop functions

In this appendix we define the relevant loop functions that contribute to the amplitudes of flavor violating leptonic process $BR(\tau \rightarrow \mu \gamma)$ as presented in the appendix of [30]

$$x_L = \frac{M_1^2}{m_L^2}, \quad x_R = \frac{M_1^2}{m_R^2}, \quad y_L = \frac{|\mu|^2}{m_L^2}, \quad y_R = \frac{|\mu|^2}{m_R^2}$$

(D.1)

$I_{B,R}$ and $I_R$ are defined as follows,

$$I_{B,R}(M_1^2, m_L^2, m_R^2) = -\frac{1}{m_R^2 - m_L^2} \left[ y_R h_1(x_R) - \frac{y_L g_1(x_L) - y_R g_1(x_R)}{1 - \frac{m_L^2}{m_R^2}} \right]$$

(D.2)

$$I_R(m_R^2, M_1^2, \mu^2) = \frac{1}{m_R^2 y_R - x_R} \left[ h_1(x_R) - h_1(y_R) \right]$$

(D.3)

The functions $g_1$ and $h_1$ are defined as follows,

$$g_1(x) = \frac{1 - x^2 + 2x \ln(x)}{(1 - x)^3}, \quad h_1(x) = \frac{1 + 4x - 5x^2 + (2x^2 + 4x) \ln(x)}{(1 - x)^4}$$

(D.4)
E Cross-sections

In this appendix we present the approximate formulae for the relevant cross sections. We do not attempt to discuss a complete comparison of the analytical expressions and full numerical results in the present paper, that is left for an upcoming publication. These expressions generalize the existing expressions \[E.1\] in the literature to include full flavor violation in the sleptonic sector. The expressions are presented only for the dominant channels and in the limit \(m_\tau, m_\mu \rightarrow 0\). More detailed expressions and their simplifications will be discussed elsewhere \[E.1\].

\[
\sigma_{\text{channel}} = \frac{\text{Numerator}}{\text{Denominator}} \quad (E.1)
\]

E.1 \(\bar{l}_1 l_1 \rightarrow \tau \tau\)

The cross-section of \(\bar{l}_1 l_1 \rightarrow \tau \tau\) process is as follows. This process involves \(t\)- and \(u\)-channel \(\tilde{\chi}_1^0\) exchange. In the following and in rest of the cross-sections \(e\) is the electric charge, \(\theta_W\) is the weak mixing angle and \(M_W\) is the mass of the W-boson. We get the simplified form of the above cross-section in the limit of \(m_\tau \rightarrow 0\) as below, where the numerator is

\[
e^4 \left[ - \sum_+ \Sigma_+^2 \sqrt{s(s - 4m_{l_1}^2)} - \sum_- \Sigma_-^2 (s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2) \\
\times \log \left| \frac{s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2 - \sqrt{s(s - 4m_{l_1}^2)}}{s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2 + \sqrt{s(s - 4m_{l_1}^2)}} \right| \\
\times \left\{ 2\sum_+ \Sigma_+^2 m_{\tilde{\chi}_1^0}^4 + 2\sum_- \Sigma_-^2 m_{l_1}^4 + m_{\tilde{\chi}_1^0}^2 \left( (\sum_+ \Sigma_+^2)^2 - 4\sum_- \Sigma_-^2 m_{l_1}^2 \right) \right\} \\
- \frac{1}{s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2} \log \left| \frac{s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2 - \sqrt{s(s - 4m_{l_1}^2)}}{s + 2m_{\tilde{\chi}_1^0}^2 - 2m_{l_1}^2 + \sqrt{s(s - 4m_{l_1}^2)}} \right| \right]
\]

\[
\times \left\{ \frac{2\sum_+ \Sigma_+^2 m_{\tilde{\chi}_1^0}^4}{2 \left( m_{\tilde{\chi}_1^0}^4 + m_{l_1}^4 + m_{\tilde{\chi}_1^0}^2 (s - 2m_{l_1}^2) \right)} \right\} \left\{ 4\sum_+ \Sigma_+^2 m_{\tilde{\chi}_1^0}^4 \\
+ 4\sum_+ \Sigma_+^2 m_{l_1}^4 - (\sum_+ \Sigma_+^2)^2 m_{\tilde{\chi}_1^0}^2 s \\
+ 2\sum_+ \Sigma_+^2 m_{\tilde{\chi}_1^0}^2 s - 8\sum_+ \Sigma_+^2 m_{\tilde{\chi}_1^0}^2 m_{l_1}^2 \right\} \right\} 
\]

(E.2)

And the denominator is

\[
32\pi s M_W^4 \cos^4 \theta_W \sin^4 \theta_W (s - 4m_{l_1}^2) \quad (E.3)
\]

Following appendix C the coupling structure is:
\[ \bar{\tau} - \bar{\chi}_1^0 - \bar{l}_1: \]

\[ K_1 \left( \Sigma_+ P_R + \Sigma_- P_L \right) \quad (E.4) \]

where

\[ \Sigma_+ = \left[ \cos \theta_W \ ON(1,2) + \sin \theta_W \ ON(1,1) \right] \cos \beta \ M_W \ U(1,3) \quad (E.5) \]

and

\[ \Sigma_- = -2 \sin \theta_W \ M_W \ \cos \beta \ U(1,6) \ ON(1,1) \quad (E.6) \]

Where \( K_1 \) is already defined in eq. (C.4).

E.2 \( \bar{l}_1 \bar{l}_1 \rightarrow \mu \tau \)

The simplified form of the \( \bar{l}_1 \bar{l}_1 \rightarrow \mu \tau \) cross-section in the limit of \( m_\tau, m_\mu \rightarrow 0 \) is calculated below. This process involves \( t- \) and \( u- \)channel \( \chi_1^0 \) exchange. The numerator of the cross-section is

\[ e^4 \left[ - (\Sigma_+^2 \Lambda_+^2 + \Sigma_-^2 \Lambda_+^2) \sqrt{s(s - 4m_{\chi_1^0}^2)} - (\Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2) \right. \]

\[ \times \left( s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2 \right) \log \left| \frac{s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2 - \sqrt{s(s - 4m_{\chi_1^0}^2)}}{s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2 + \sqrt{s(s - 4m_{\chi_1^0}^2)}} \right| \]

\[ - \frac{2}{s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2} \log \left| \frac{s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2 - \sqrt{s(s - 4m_{l_1}^2)}}{s + 2m_{\chi_1^0}^2 - 2m_{l_1}^2 + \sqrt{s(s - 4m_{l_1}^2)}} \right| \]

\[ \times \left\{ \left( \Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2 \right) m_{l_1}^4 + \left( \Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2 \right) m_{l_1}^4 \right. \]

\[ + m_{\chi_1^0}^2 \left( \left( \Sigma_+^2 + \Sigma_-^2 \right) \left( \Lambda_-^2 + \Lambda_+^2 \right) s - 2 \left( \Sigma_+^2 \Lambda_+^2 + \Sigma_-^2 \Lambda_-^2 \right) m_{l_1}^2 \right) \}

\[ - \frac{\sqrt{s(s - 4m_{\chi_1^0}^2)}}{m_{\chi_1^0}^4 + m_{l_1}^4 + m_{\chi_1^0}^2 \left( s - 2m_{l_1}^2 \right)} \left\{ 2 \left( \Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2 \right) m_{l_1}^4 \right. \]

\[ + 2 \left( \Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2 \right) m_{l_1}^4 + \left( \Sigma_+^2 \left( 2\Lambda_-^2 - \Lambda_+^2 \right) - \Sigma_-^2 \left( \Lambda_-^2 - 2\Lambda_+^2 \right) \right) m_{\chi_1^0}^2 s \]

\[ \left. - 4 \left( \Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2 \right) m_{\chi_1^0}^2 m_{l_1}^2 \right\} \quad (E.7) \]

And the denominator is

\[ 32\pi s \ M_W^4 \ \cos^4 \beta \ \cos^4 \theta_W \ \sin^4 \theta_W \ \left( s - 4m_{l_1}^2 \right) \quad (E.8) \]

Here the coupling structure is:
\[ \vec{\mu} - \vec{\chi}_1^0 - \vec{l}_1: \]
\[ K_1 (\Lambda_+ P_R + \Lambda_- P_L) \tag{E.9} \]
where
\[ \Lambda_+ = [\cos \theta_W \ ON(1, 2) + \sin \theta_W \ ON(1, 1)] \cos \beta \ M_W \ U(1, 2) \tag{E.10} \]
and
\[ \Lambda_- = -2 \sin \theta_W \ M_W \ \cos \beta \ U(1, 5) \ ON(1, 1) \tag{E.11} \]

**E.3 \ \chi_1^0 \chi_1^0 \rightarrow \tau/\mu \tau**

In the limit \( m_\tau \rightarrow 0 \) the cross-section for \( \chi_1^0 \chi_1^0 \rightarrow \tau \tau \) is calculated. This process involves \( t- \) and \( u- \) channel \( \vec{l}_1 \) exchange. The numerator is
\[ e^4 \left\{ \frac{\sqrt{s(s-4m_{\chi_1}^2)}}{s m_{l_i}^2 + (m_{\chi_1}^2 - m_{l_i}^2)^2} \left\{ (\Sigma_+^4 + 4\Sigma_+^2 \Sigma_+^2 + \Sigma_+^4) s m_{l_i}^2 + 2(\Sigma_+^4 + 3\Sigma_+^2 \Sigma_+^2 + \Sigma_+^4) \right\} \right. \]
\[ \times \left( m_{\chi_1}^2 - m_{l_i}^2 \right)^2 \right\} - \frac{2}{-s + 2m_{\chi_1}^2 - 2m_{l_i}^2} \log \left[ \frac{\sqrt{s(s-4m_{\chi_1}^2)}}{s(s-4m_{\chi_1}^2)} + (s-2m_{\chi_1}^2 + 2m_{l_i}^2) \right] \]
\[ \times \left\{ s(-2\Sigma_+^2 \Sigma_+^2 m_{\chi_1}^2 + (\Sigma_+^4 + 4\Sigma_+^2 \Sigma_+^2 + \Sigma_+^4) m_{l_i}^2 \right) + 2(\Sigma_+^4 + 3\Sigma_+^2 \Sigma_+^2 + \Sigma_+^4) \right\} \]
\[ \times \left( m_{\chi_1}^2 - m_{l_i}^2 \right)^2 \right\} \tag{E.12} \]

And the denominator is
\[ 128\pi s M_W^4 \cos^4 \beta \sin^4 \theta_W \ M_W (s - 4m_{\chi_1}^2) \tag{E.13} \]

Whereas in the limit \( m_\tau, m_\mu \rightarrow 0 \) the cross-section for \( \chi_1^0 \chi_1^0 \rightarrow \mu \tau \) is calculated. This process involves \( t- \) and \( u- \) channel \( \vec{l}_1 \) exchange. The numerator is
\[ e^4 \left\{ \frac{\sqrt{s(s-4m_{\chi_1}^2)}}{s m_{l_i}^2 + (m_{\chi_1}^2 - m_{l_i}^2)^2} \left\{ (\Sigma_+^2 (2\Lambda_-^2 + \Lambda_+^2) + \Sigma_-^2 (\Lambda_-^2 + 2\Lambda_+^2) \right\} s m_{l_i} \right. \]
\[ + \left\{ \Sigma_+^2 (3\Lambda_-^2 + 2\Lambda_+^2) + \Sigma_-^2 (2\Lambda_-^2 + 3\Lambda_+^2) \right\} (m_{\chi_1}^2 - m_{l_i}^2)^2 \right\} \]
\[ - \frac{2}{-s + 2m_{\chi_1}^2 - 2m_{l_i}^2} \log \left[ \frac{\sqrt{s(s-4m_{\chi_1}^2)}}{s(s-4m_{\chi_1}^2)} + (s-2m_{\chi_1}^2 + 2m_{l_i}^2) \right] \]
\[ \times \left\{ \Sigma_+^2 (3\Lambda_-^2 + 2\Lambda_+^2) + \Sigma_-^2 (2\Lambda_-^2 + 3\Lambda_+^2) \right\} (m_{\chi_1}^2 - m_{l_i}^2)^2 \]
\[ + s \left\{ (\Sigma_+^2 \Lambda_-^2 + \Sigma_-^2 \Lambda_+^2) m_{\chi_1}^2 + (\Sigma_+^2 (2\Lambda_-^2 + \Lambda_+^2) + \Sigma_-^2 (\Lambda_-^2 + 2\Lambda_+^2)) m_{l_i}^2 \right\} \right\} \tag{E.14} \]
And the denominator is

\[ 128 \pi s M_W^4 \cos^4 \beta \sin^4 \theta_W \cos^4 \theta_W (s - 4m_{\chi_0}^2) \]  \quad (E.15)

**E.4** \( \tilde{\chi}_1^0 \rightarrow \gamma \tau / \mu \)

In the limit \( m_\tau \to 0 \) the cross-section for \( \tilde{\chi}_1^0 \tilde{l}_1 \rightarrow \gamma \tau \) is calculated. This process involves \( s \)-channel \( \tau \) mediation and \( t \)-channel \( \tilde{l}_1 \) exchange. The numerator is

\[
\left( \Sigma^2_+ + \Sigma^2_- \right) e^4 \left\{ \log \frac{m_{\chi_0}^2 - (s + m_{l_1}^2)}{m_{\chi_0}^2 - (s + m_{l_1}^2) + \sqrt{m_{\chi_0}^4 + (-s + m_{l_1}^2)^2 - 2m_{\chi_0}^2(s + m_{l_1}^2)}} \right. \\
\left. \times s\left( m_{\chi_0}^2 - 3m_{l_1}^2 \right) + \left( s - 2m_{\chi_0}^2 + 2m_{l_1}^2 \right) \sqrt{m_{\chi_0}^4 + (-s + m_{l_1}^2)^2 - 2m_{\chi_0}^2(s + m_{l_1}^2)} \right\} \quad (E.16)
\]

And the denominator is

\[
32 \pi s M_W^2 \cos^2 \beta \sin^2 \theta_W \cos^2 \theta_W \left\{ m_{\chi_0}^4 + (-s + m_{l_1}^2)^2 - 2m_{\chi_0}^2(s + m_{l_1}^2) \right\} \]  \quad (E.17)

Whereas in the limit \( m_\mu \to 0 \) the cross-section for \( \tilde{\chi}_1^0 \tilde{l}_1 \rightarrow \gamma \mu \) is calculated. This process involves \( s \)-channel \( \mu \) mediation and \( t \)-channel \( \tilde{l}_1 \) exchange. The numerator is

\[
\left( A^2_+ + A^2_- \right) e^4 \left\{ \log \frac{m_{\chi_0}^2 - (s + m_{l_1}^2)}{m_{\chi_0}^2 - (s + m_{l_1}^2) + \sqrt{m_{\chi_0}^4 + (-s + m_{l_1}^2)^2 - 2m_{\chi_0}^2(s + m_{l_1}^2)}} \right. \\
\left. \times s\left( m_{\chi_0}^2 - 3m_{l_1}^2 \right) + \left( s - 2m_{\chi_0}^2 + 2m_{l_1}^2 \right) \sqrt{m_{\chi_0}^4 + (-s + m_{l_1}^2)^2 - 2m_{\chi_0}^2(s + m_{l_1}^2)} \right\} \quad (E.18)
\]

And the denominator is

\[
32 \pi s M_W^2 \cos^2 \beta \sin^2 \theta_W \cos^2 \theta_W \left\{ m_{\chi_0}^4 + \left( -s + m_{l_1}^2 \right)^2 - 2m_{\chi_0}^2 \left( s + m_{l_1}^2 \right) \right\} \]  \quad (E.19)

**References**

[1] G. Jungman, M. Kamionkowski and K. Griest, *Supersymmetric dark matter*, *Phys. Rept.* 267 (1996) 195 [hep-ph/9506380] [spire].

[2] H. Goldberg, *Constraint on the photino mass from cosmology*, *Phys. Rev. Lett.* 50 (1983) 1419 [Erratum ibid. 103 (2009) 099905] [spire].

[3] J.R. Ellis, J. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, *Supersymmetric relics from the big bang*, *Nucl. Phys.* B 238 (1984) 453 [spire].

[4] P.H. Chankowski, J.R. Ellis, K.A. Olive and S. Pokorski, *Cosmological fine tuning, supersymmetry and the gauge hierarchy problem*, *Phys. Lett.* B 452 (1999) 28 [hep-ph/9811284] [spire].
[5] D. Larson et al., Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Power Spectra and WMAP-Derived Parameters, *Astrophys. J. Suppl.* **192** (2011) 16 [arXiv:1001.4635] [inSPIRE].

[6] N. Arkani-Hamed, A. Delgado and G. Giudice, The Well-tempered neutralino, *Nucl. Phys. B* **741** (2006) 108 [hep-ph/0601041] [inSPIRE].

[7] H. Baer, C. Balázs, A. Belyaev, T. Krupovnickas and X. Tata, Updated reach of the CERN LHC and constraints from relic density, $b \to s\gamma$ and $a(\mu)$ in the mSUGRA model, *JHEP* **06** (2003) 054 [hep-ph/0304303] [inSPIRE].

[8] A. Djouadi, M. Drees and J.-L. Kneur, Updated constraints on the minimal supergravity model, *JHEP* **03** (2006) 033 [hep-ph/0602001] [inSPIRE].

[9] L. Calibbi, Y. Mambrini and S. Vempati, SUSY-GUTs, SUSY-seesaw and the neutralino dark matter, *JHEP* **09** (2007) 081 [arXiv:0704.3518] [inSPIRE].

[10] V. Barger, D. Marfatia and A. Mustafayev, Neutrino sector impacts SUSY dark matter, *Phys. Rev. D* **76** (2007) 055008 [arXiv:0705.0921] [inSPIRE].

[11] J. Esteves, J. Romao, M. Hirsch, F. Staub and W. Porod, Supersymmetric type-III seesaw: lepton flavour violating decays and dark matter, *Phys. Rev. D* **83** (2011) 013003 [arXiv:1010.6000] [inSPIRE].

[12] E. Dudas, S. Pokorski and C.A. Savoy, Soft scalar masses in supergravity with horizontal $U(1)_x$ gauge symmetry, *Phys. Lett. B* **369** (1996) 255 [hep-ph/9509410] [inSPIRE].

[13] L. Calibbi, A. Faccia, A. Masiero and S. Vempati, Lepton flavour violation from SUSY-GUTs: Where do we stand for MEG, PRISM/PRIME and a super flavour factory, *Phys. Rev. D* **74** (2006) 116002 [hep-ph/0605139] [inSPIRE].
[22] R. Barbieri, L.J. Hall and A. Romanino, *Consequences of a U(2) flavor symmetry*, *Phys. Lett. B* **401** (1997) 47 [hep-ph/9702315] [nSPIRE].

[23] T. Kobayashi, H. Nakano, H. Terao and K. Yoshioka, *Flavor violation in supersymmetric theories with gauged flavor symmetries*, *Prog. Theor. Phys.* **110** (2003) 247 [hep-ph/0211347] [nSPIRE].

[24] P.H. Chankowski, K. Kowalska, S. Lavignac and S. Pokorski, *Update on fermion mass models with an anomalous horizontal U(1) symmetry*, *Phys. Rev. D* **71** (2005) 055004 [hep-ph/0501071] [nSPIRE].

[25] S. Antusch, S.F. King, M. Malinsky and G.G. Ross, *Solving the SUSY Flavour and CP Problems with Non-Abelian Family Symmetry and Supergravity*, *Phys. Lett. B* **401** (1997) [hep-ph/9702315] [nSPIRE].

[26] C.A. Scrucca, *Soft masses in superstring models with anomalous U(1) symmetries*, *JHEP* **12** (2007) 092 [arXiv:0710.5105] [nSPIRE].

[27] J. Esteves et al., *LHC and lepton flavour violation phenomenology of a left-right extension of the MSSM*, *JHEP* **12** (2010) 077 [arXiv:1011.0348] [nSPIRE].

[28] J. Esteves et al., *Dark matter and LHC phenomenology in a left-right supersymmetric model*, *JHEP* **01** (2012) 095 [arXiv:1109.6478] [nSPIRE].

[29] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi and T. Yanagida, *Lepton flavor violation in the supersymmetric standard model with seesaw induced neutrino masses*, *Phys. Lett. B* **357** (1995) 579 [hep-ph/9501407] [nSPIRE].

[30] I. Masina and C.A. Savoy, *Sleptonarium: Constraints on the CP and flavor pattern of scalar lepton masses*, *Nucl. Phys. B* **661** (2003) 365 [hep-ph/0211283] [nSPIRE].

[31] P. Paradisi, *Constraints on SUSY lepton flavor violation by rare processes*, *JHEP* **10** (2005) 006 [hep-ph/0505046] [nSPIRE].

[32] J. Hisano, R. Kitano and M.M. Nojiri, *Slepton oscillation at large hadron collider*, *Phys. Rev. D* **65** (2002) 116002 [hep-ph/0202129] [nSPIRE].

[33] J. Hisano, M.M. Nojiri and W. Sreethawong, *Discriminating Electroweak-ino Parameter Ordering at the LHC and Its Impact on LFV Studies*, *JHEP* **06** (2009) 044 [arXiv:0812.4498] [nSPIRE].

[34] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, *Phys. Rev. D* **43** (1991) 3191 [nSPIRE].

[35] G. Belanger et al., *Indirect search for dark matter with MicrOMEGAs2.4*, *Comput. Phys. Commun.* **182** (2011) 842 [arXiv:1004.1092] [nSPIRE].

[36] M. Ciuchini et al., *Soft SUSY breaking grand unification: Leptons versus quarks on the flavor playground*, *Nucl. Phys. B* **783** (2007) 112 [hep-ph/0702144] [nSPIRE].

[37] *Particle Data Group* collaboration, K. Nakamura et al., *Review of particle physics*, *J. Phys. G* **37** (2010) 075021 [nSPIRE].

[38] https://twiki.cern.ch/twiki/bin/view/AtlasPublic,
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG.

[39] J.R. Ellis, T. Falk, K.A. Olive and Y. Santoso, *Exploration of the MSSM with nonuniversal Higgs masses*, *Nucl. Phys. B* **652** (2003) 259 [hep-ph/0210205] [nSPIRE].
[40] H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, Direct, indirect and collider detection of neutralino dark matter in SUSY models with non-universal Higgs masses, JHEP 07 (2005) 065 [hep-ph/0504001] [inSPIRE].

[41] J.R. Ellis, K.A. Olive and P. Sandick, Varying the Universality of Supersymmetry-Breaking Contributions to MSSM Higgs Boson Masses, Phys. Rev. D 78 (2008) 075012 [arXiv:0805.2343] [inSPIRE].

[42] J.R. Ellis, S. King and J. Roberts, The Fine-Tuning Price of Neutralino Dark Matter in Models with Non-Universal Higgs Masses, JHEP 04 (2008) 099 [arXiv:0711.2741] [inSPIRE].

[43] L. Roszkowski, R. Ruiz de Austri, R. Trotta, Y.-L.S. Tsai and T.A. Varley, Global fits of the Non-Universal Higgs Model, Phys. Rev. D 83 (2011) 015014 [arXiv:0903.1279] [inSPIRE].

[44] D. Das, A. Goudelis and Y. Mambrini, Exploring SUSY light Higgs boson scenarios via dark matter experiments, JCAP 12 (2010) 018 [arXiv:1007.4812] [inSPIRE].

[45] D. Chowdhury and S.K. Vempati, Flavor Effects in the Neutralino Cross-sections in the Early Universe, in preparation.

[46] I. Hinchliffe and F. Paige, Lepton flavor violation at the CERN LHC, Phys. Rev. D 63 (2001) 115006 [hep-ph/0010086] [inSPIRE].

[47] B. Allanach, J. Conlon and C. Lester, Measuring Snuon-Selectron Mass Splitting at the CERN LHC and Patterns of Supersymmetry Breaking, Phys. Rev. D 77 (2008) 076006 [arXiv:0801.3666] [inSPIRE].

[48] A.J. Buras, L. Calibbi and P. Paradisi, Slepton mass-splittings as a signal of LFV at the LHC, JHEP 06 (2010) 042 [arXiv:0912.1309] [inSPIRE].

[49] A. Bartl et al., Test of lepton flavor violation at LHC, Eur. Phys. J. C 46 (2006) 783 [hep-ph/0510074] [inSPIRE].

[50] M.M. Nojiri, Polarization of τ lepton from scalar τ decay as a probe of neutralino mixing, Phys. Rev. D 51 (1995) 6281 [hep-ph/9412374] [inSPIRE].

[51] M.M. Nojiri, K. Fujii and T. Tsukamoto, Confronting the minimal supersymmetric standard model with the study of scalar leptons at future linear e+e− colliders, Phys. Rev. D 54 (1996) 6756 [hep-ph/9606370] [inSPIRE].

[52] M. Guchait and D. Roy, Using τ polarization as a distinctive SUGRA signature at LHC, Phys. Lett. B 541 (2002) 356 [hep-ph/0205015] [inSPIRE].

[53] K. Hamaguchi, Y. Kuno, T. Nakaya and M.M. Nojiri, A Study of late decaying charged particles at future colliders, Phys. Rev. D 70 (2004) 115007 [hep-ph/0409248] [inSPIRE].

[54] R. Godbole, M. Guchait and D. Roy, Using Tau Polarization to probe the Stau Co-annihilation Region of mSUGRA Model at LHC, Phys. Rev. D 79 (2009) 095015 [arXiv:0807.2390] [inSPIRE].

[55] A. Brignole and A. Rossi, Anatomy and phenomenology of mu-tau lepton flavor violation in the MSSM, Nucl. Phys. B 701 (2004) 3 [hep-ph/0404211] [inSPIRE].

[56] D. Chowdhury, R. Garani and S.K. Vempati, SUSEFLAV: Program for supersymmetric mass spectra with seesaw mechanism and rare lepton flavor violating decays, arXiv:1109.3551 [inSPIRE].
[57] D.M. Pierce, J.A. Bagger, K.T. Matchev and R.-j. Zhang, *Precision corrections in the minimal supersymmetric standard model*, Nucl. Phys. B 491 (1997) 3 [hep-ph/9606211] [inSPIRE].

[58] S. Heinemeyer, W. Hollik and G. Weiglein, *The Mass of the lightest MSSM Higgs boson: A Compact analytical expression at the two loop level*, Phys. Lett. B 455 (1999) 179 [hep-ph/9903404] [inSPIRE].

[59] A. Pukhov et al., *CompHEP: A Package for evaluation of Feynman diagrams and integration over multiparticle phase space*, hep-ph/9908288 [inSPIRE].

[60] LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL collaboration, R. Barate et al., *Search for the standard model Higgs boson at LEP*, Phys. Lett. B 565 (2003) 61 [hep-ex/0306033] [inSPIRE].

[61] J. Frere, D. Jones and S. Raby, *Fermion Masses and Induction of the Weak Scale by Supergravity*, Nucl. Phys. B 222 (1983) 11 [inSPIRE].

[62] L. Álvarez-Gaumé, J. Polchinski and M.B. Wise, *Minimal Low-Energy Supergravity*, Nucl. Phys. B 221 (1983) 495 [inSPIRE].

[63] M. Claudson, L.J. Hall and I. Hinchliffe, *Low-Energy Supergravity: False Vacua and Vacuous Predictions*, Nucl. Phys. B 228 (1983) 501 [inSPIRE].

[64] T. Nihei, L. Roszkowski and R. Ruiz de Austri, *Exact cross-sections for the neutralino slepton coannihilation*, JHEP 07 (2002) 024 [hep-ph/0206266] [inSPIRE].