Letter

Leptogenesis in supersymmetry with one L violating coupling

Rathin Adhikari[1,a], **Arnab Dasgupta**[2,b]

[1] Centre for Theoretical Physics, Jamia Millia Islamia (Central University), New Delhi 110025, India
[2] School of Liberal Arts, Seoul-Tech, Seoul 139-743, South Korea

Abstract We have shown a new scenario of successful leptogenesis with one L violating coupling and a relative Majorana phase playing the role of CP violation. This is in contrast to the usual consideration of Feynman diagram with at least two L violating couplings. We have considered R-parity violating minimal supersymmetric standard model (MSSM) for leptogenesis at TeV scale. This scenario is also consistent with generating light neutrino mass if asymmetry is generated through semileptonic λ' coupling.

1 Introduction

There is asymmetry in the number density of baryons (n_B) and antibaryons ($n_{\bar{B}}$) in our observed universe [1,2] and one may consider baryogenesis or leptogenesis mechanism [3] to explain such asymmetry. In the latter case the lepton number asymmetry could result in baryon number asymmetry in presence of sphalerons.

For successful baryogenesis/leptogenesis mechanism three basic Sakharov's conditions [4]: (1) Presence of baryon number (B) or lepton number (L) violating interactions (2) C and CP violating physical process and (3) departure of those physical processes from thermal equilibrium, are to be fulfilled. Non-zero CP asymmetry requires interference of tree level and higher order Feynman diagrams related to those physical process. However, to get non-zero B or L asymmetry certain conditions [5,6] on higher order Feynman diagram are to be satisfied. According to Nanopoulos-Weinberg theorem [5] such diagram should require at least two B or L violating couplings for the decaying particle having only B or L violating decay modes [7]. As considering more B or L violating couplings in Feynman diagram reduces the asymmetry due to smallness of such couplings, it would be more appropriate to find out baryogenesis or leptogenesis mech-

anism where restriction of this theorem could be avoided. This could be possible if the decaying particle generating asymmetry has B or L conserving decay modes also [6]. We have considered leptogenesis mechanism in the context of R parity violating Minimal Supersymmetric Standard model where next to lightest neutralino could have this property of having both L violating and L conserving decay modes as shown in Figs. 1 and 2. Here, we have considered only one L violating coupling in Fig. 1 to produce L asymmetry which does not contradict the Nanopoulos-Weinberg theorem [6]. In case of asymmetry generated by lightest neutralino which does not have L conserving decay modes, there should be more than one L violating coupling. As for example, in one work [8] related to lightest neutralino decay three L violating couplings are required in higher order diagram.

Another condition on higher order diagram is as follows: The interaction between intermediate on-shell particles and the final particles should correspond to a net change in baryon/lepton number [6]. In other words, B or L violating coupling should be present on the right of the 'cut' in the higher order diagram ('cut' on the internal line is possible when on-shell condition is satisfied indicating presence of imaginary part of loop integral which is required for CP asymmetry) with net change in B or L due to all such couplings on the right with final states. This is essential to have non-vanishing total B or L asymmetry after summing over all possible intermediate and final states generated due to decay. One may get non-zero asymmetry from the interference of tree and higher order diagram without right of the 'cut' condition, but it would vanish if other diagrams with all possible intermediate and final states are considered. The cases where some authors have found vanishing of total asymmetry [9–11] are examples of this feature. In our case in leptogenesis, above-mentioned condition is satisfied in the higher order Feynman diagram for neutralino decay as shown in Fig. 1.

[a] e-mail: rathin@ctp-jamia.res.in

[b] e-mail: arnabdasgupta@protonmail.ch (corresponding author)
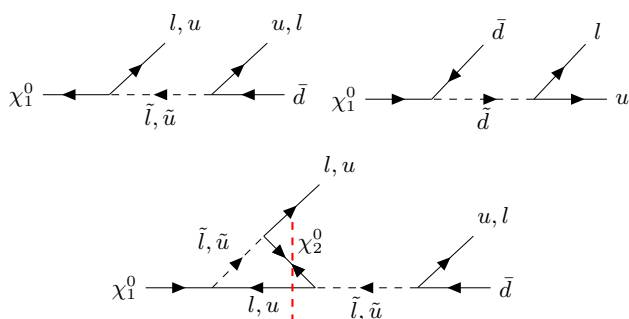
Fig. 1 The tree level and next higher order diagrams giving rise to leptonic asymmetry. Lepton number violating coupling is on the right of the vertical 'cut' shown in second diagram[1]

2 Low scale leptogenesis in MSSM

We have shown in R parity violating MSSM, leptogenesis could be possible at low energy scale ($\mathcal{O}$ TeV). There are some interesting works on low scale leptogenesis [12] considering non-supersymmetric models [13–23] and supersymmetric models [8,24–32]. In non-supersymmetric models, in resonant leptogenesis scenario [13–21] the asymmetry is enhanced by resonance through self-energy effects. But certain amount of fine tuning is required. At least, masses of the two heavy neutrinos are required to be quasi-degenerate with their mass difference of the order of their decay widths. In heavy neutrino oscillation scenario [22] of leptogenesis, the Yukawa couplings of electroweak singlet neutrinos are required to be very small ($\sim 10^{-8}$) and near mass degeneracy of heavy neutrinos are required. However, it was shown later [23] that such mass degeneracy may not be required but then the Yukawa couplings are somewhat higher than what is in general, considered for most of the points in parameter space for see-saw mechanism. In works related to supersymmetric models, the minimal version of the model – the MSSM with explicit R parity violation [33–35], seems to be inadequate for the generation of asymmetry. Due to that it has been modified in the scalar sector by introducing new scalar field or has been modified by considering the R violating interactions with non-holomorphic terms in the superpotential. Even for leptogenesis at high scale ($\sim 10^6$ GeV), in interesting soft leptogenesis scenario in non-minimal supersymmetric models, some fine-tuning is required with masses of sneutrinos to avoid the gravitino over-abundance problem [27–30]. Otherwise, generic trilinear soft supersymmetry breaking couplings are to be assumed [31]. However, here we have shown the possibility of successful leptogenesis at low energy scale in the minimal version itself, which is devoid of aforementioned problems.
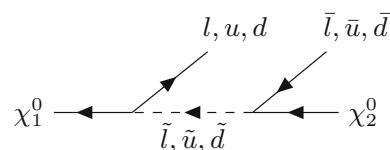
In MSSM with explicit R-parity violation [33–35], L violation could come from the following trilinear R-parity violating terms in the superpotential:

$$W_{RPV} = \sum_{i,j,k} \left(\frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c \right), \quad (1)$$

where L_i and Q_i are $SU(2)$ doublet lepton and quark superfield respectively and E_i and D_i are $SU(2)$ singlet charged lepton and down type quark superfield respectively. We have assumed that the bilinear L violating term in the superpotential could be rotated away with suitable field redefinition. However, in general, such couplings are expected to be very small due to the cosmological bound on the light neutrino masses [36–42]. We have considered only the presence of non-zero λ'_{ijk} couplings in our numerical analysis. Similar results are expected to follow if one considers both λ_{ijk} and λ'_{ijk} couplings or any one of those couplings as non-zero for the generation of leptonic and hence baryonic asymmetry. However, if one considers any of these or both such couplings for the generation of active neutrino mass then those neutrinos are of Majorana type. In that case, lepton numbers of neutrinos are not well-defined. But in generating leptonic asymmetry with λ_{ijk} couplings through the decays of neutralino, lepton number of neutrinos and antineutrinos are required. But for λ'_{ijk} couplings, such role is played by the lepton number of charged leptons and anti-leptons. So if same coupling is assumed to be connected with leptonic asymmetry as well as neutrino mass then that should be λ'_{ijk} couplings as considered in this work.

In our scenario the leptonic asymmetry is generated above electroweak symmetry breaking scale. In that case, the next to lightest neutralino (which is only bino without any wino or Higgsino component) has only three body decay modes. The decay of next to lightest neutralino (χ_1^0) occurs through L violating decay mode $\chi_1^0 \rightarrow u l \bar{d}$ and L conserving decay mode $\chi_1^0 \rightarrow \chi_2^0 l \bar{l}(q\bar{q})$. The decay process $\chi_1^0 \rightarrow u l \bar{d}$ with $\Delta L = 1$ and its conjugate process $\chi_1^0 \rightarrow \bar{u} d \bar{l}$ generates asymmetry with λ'_{ijk} coupling. For L violating decay the tree level diagrams and next higher order Feynman diagrams with one L violating couplings are shown in Fig. 1 in which charged left slepton $\tilde{l}$ and $\tilde{u}$ are the superpartner of left charged lepton l and left u quark respectively and $\tilde{d}$ is the superpartner of right d quark. In the loop diagram, there is no right $\tilde{d}$ in the internal line, as this does not interact with χ_2^0. The L conserv-

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[1] Readers may note that contrary to standard notations, we consider χ_1^0 as next to lightest neutralino and χ_2^0 as the lightest neutralino.

Fig. 2 L conserving decays of χ_1^0

ing decays are shown in Fig. 2 which are mediated by left as well as right squarks and sleptons. There is also diagram with l, u, d and $\bar{l}, \bar{u}, \bar{d}$ interchanged with opposite arrows which is not shown.

We consider the neutralino mass matrix above electroweak symmetry breaking scale where the leptonic asymmetry is expected to be converted to baryonic asymmetry in presence of sphalerons as discussed later. The mass matrix is given by

$$
\mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & 0 & 0 \\ 0 & M_2 & 0 & 0 \\ 0 & 0 & 0 & -\mu \\ 0 & 0 & -\mu & 0 \end{pmatrix}; \qquad \begin{array}{l} m_{\chi_1^0} = |M_1| \\ m_{\chi_2^0} = |M_2| \\ m_{\chi_3^0} = |\mu| \\ m_{\chi_4^0} = |\mu| \end{array} \qquad (2)
$$

where μ is the Higgsino mass parameter and M_1 and M_2 are the $U(1)$ and $SU(2)$ gaugino mass parameters respectively. One may note that there are no gaugino-Higgsino mixing in the above mass matrix as that occurs due to electroweak symmetry breaking when Higgs scalar is replaced by its vacuum expectation value in Higgs-gaugino-Higgsino interaction. We have considered $|\mu| > (|M_1|, |M_2|)$ as otherwise next to lightest neutralino would decay dominantly to higgs and lightest neutralino. Then it will be hard to get enough leptonic asymmetry from its L violating decay modes. Also we consider $|M_1| > |M_2|$ in our work as otherwise for $|M_1| < |M_2|$ there would be annihilation of the next to lightest neutralino to W^+W^-. The dominant decay channel for $\chi_{3,4}^0$ corresponds to decaying to lightest higgs and other lighter neutralinos and as such the leptonic asymmetry generated by these are expected to be negligible. Furthermore, any asymmetry generated by these or generated at high scale by the L violating decay of heavy particles will be washed out by the asymmetry generated at low scale by the decay of lighter neutralino. The lighter two neutralinos do not decay to Higgs scalar because of the above structure of neutralino mass matrix. χ_2^0 being the lightest neutralino for above mass matrix, has no L conserving decay mode and has only L violating decay modes. So according to our earlier discussion, the next to lightest neutralino χ_1^0 with both L conserving and L violating decay modes, turns out to be the only suitable neutralino for creating sufficient asymmetry with one L violating coupling.

To obtain asymmetry, CP violation is also required. In our work, this comes due to Majorana nature of neutralino fields. For CP violating phase, the relevant part in the above complex symmetric neutralino mass matrix, is the upper left 2×2 block. This block contains complex mass parameters M_1 and M_2. This block is decoupled from the rest part of mass matrix so far diagonalisation is concerned. So, lighter two neutalinos χ_1 and χ_2 states could contain at least one relative Majorana phase $e^{-i\phi}$ as diagonal phase matrix in the neutralino mixing matrix. This is unlike CKM mixing matrix

in quark sector where three fields are necessary for CP violating phase. This Majorana phase will give non-zero CP violating phase $e^{-i2\phi}$ in the amplitude of second diagram shown in Fig. 1. This happens due to the presence of clashing arrows on propagator χ_2 consistent with its Majorana nature. Now the asymmetry comes from the interference of tree and next higher order diagram as shown in Fig. 1 and this phase gives a factor of $\sin 2\phi$ in the CP asymmetry. One could have considered such Majorana phases to be present in L conserving MSSM couplings also. L violating complex λ' coupling do not contribute to any further CP violation in generating asymmetry from the decay of χ_1. In the triangle diagram in Fig. 1, χ_1^0 is not possible in the internal line as in that case, there will be no CP violating phase in the interference term. The other two heavier neutralinos in the internal line in the triangle diagram could not be considered as the 'cut' in the diagram required for asymmetry will not be possible. So χ_2^0 on the internal line in the higher order diagram is the only option in our case. The decay of lightest neutralino χ_2^0 will not generate asymmetry through such diagrams with one L violating coupling as CP violating phase in the interference term as well as 'cut' in the diagram will not be possible simultaneously. This is consistent with our earlier discussion related to Nanopoulos-Weinberg theorem as χ_2^0 has no L conserving decay mode. However, the decay of χ_2^0 will contribute to the washout of the asymmetry generated by χ_1^0 and the corresponding term has been considered in the last Boltzman equation as shown in Eq. (5) later.

At low energy, some L conserving scatterings could result in damping of asymmetry. In R-violating MSSM such L conserving processes could be $\chi_i^0 \chi_i^0 \to W^+W^-$ through chargino as mediator and $\chi_i^0 \chi_j^0 \to l\bar{l}(\nu\bar{\nu})(q\bar{q})$ through left and right charged slepton (sneutrino) (squark) as mediator. Both types of scattering processes are 'self-quenching' [3] and Boltzman-suppressed with respect to decay process generating asymmetry at low temperature where out of equilibrium condition is satisfied. This can be seen in the Boltzman equations where thermally averaged scattering cross-sections are multiplied by the neutralino number densities also. However, without gaugino mass condition, the first process still could significantly damp the asymmetry by reducing the number density of next to lightest neutralino. This is because it would be mediated by chargino which could be not so heavy (around TeV range like neutralino) in contrast to the second process as well as the asymmetry generating decay process which are mediated by heavy slepton. With the gaugino mass condition as stated earlier after Eq. (2), the first process would not be possible for next to lightest neutralino χ_1^0 which is creating leptonic asymmetry through its decay.

There are some L violating scatterings which are of two categories: (1) $\chi_1^0 l \to \bar{u} d$ mediated by left charged slepton with $\Delta L = -1$, (2) $\chi_1^0 \bar{u} \to l\bar{d}$ mediated by left u-squark and $\chi_1^0 d \to lu$ mediated by right d-squark with $\Delta L = 1$ and

their conjugate processes. The couplings involved in these for χ_1^0 are constrained by out of equilibrium condition as those are present in χ_1^0 decay. They damp the asymmetry by reducing the number density of χ_1^0. But they could enhance or reduce the asymmetry also depending on the sign of ΔL for such processes. All these scattering processes and their conjugate and inverse processes have been taken into account in the numerical analysis. As χ_2^0 is of lighter mass than χ_1^0 in our case, we have also considered similar scatterings with replacement of χ_1^0 by χ_2^0.

If one considers Feynman diagrams with more than one non-zero L violating couplings for the neutralino decay there is scope of lightest neutralino χ_2^0 producing small CP asymmetry. But because of $\chi_2^0 \chi_2^0 \rightarrow W^+ W^-$ which reduces significantly the number density of χ_2^0, it would have insignificant effect on leptonic asymmetry at lower scale than that at which χ_1^0 produces leptonic asymmetry with one L violating coupling in the Feynman diagram in Fig. 1. However, considering different one L violating couplings in Fig. 1 one may consider different decay processes of χ_1^0 with different charged lepton and quark as decay products to get asymmetry but for simplicity we have assumed except one L violating coupling ($\lambda'_{ijk} \equiv \lambda'$) the others are smaller and ignored in asymmetry evaluation.

Considering the interference of tree and next higher order diagram in Fig. 1 one obtains the CP asymmetry parameter ϵ given by

$$\epsilon = \frac{\Gamma_{\chi_1^0 \rightarrow u l \bar{d}} - \Gamma_{\chi_1^0 \rightarrow \bar{u} d \bar{l}}}{\Gamma_{\chi_1^0 \rightarrow l u \bar{d}} + \Gamma_{\chi_1^0 \rightarrow \bar{l} d \bar{u}} + \Gamma_{\chi_1^0 \rightarrow l \bar{l} \chi_2^0} + \Gamma_{\chi_1^0 \rightarrow q \bar{q} \chi_2^0}}, \quad (3)$$

where the denominator corresponds to total decay width of next to lightest neutralino. The numerator depends on CP violating phase ϕ and one L violating coupling as

$$\left(\Gamma_{\chi_1^0 \rightarrow u l \bar{d}} - \Gamma_{\chi_1^0 \rightarrow \bar{u} d \bar{l}} \right) \propto |\lambda'|^2 \sin 2\phi.$$

The exact expressions of the numerator and denominator of ϵ are given in Appendix A in terms of the integrals which includes the factor due to three body phase space. In the numerator interference term from Fig. 1 has been taken into account in which difference of two interference terms for the decay process and its conjugate process contain the imaginary part of the loop integrals associated with higher order diagram in Fig. 1.

We have considered the thermal masses of leptons and quarks above electroweak scale given by [43]

$$m_l(z) = m_\nu(z) = \sqrt{\frac{3}{23} g^2 + \frac{1}{32} g'^2} \frac{m_{\chi_1}}{z};$$

$$m_u(z) = m_d(z) = \sqrt{\frac{1}{3} g_s + \frac{3}{16} g^2 + \frac{1}{144} g'^2} \frac{m_{\chi_1}}{z}. \quad (4)$$

where $z = \frac{m_{\chi_1}}{T}$, $g = \frac{e}{\sin \theta_W}$, $g' = \frac{e}{\cos \theta_W}$ and g_s is the strong coupling constant.

3 Estimating leptonic asymmetry and neutrino mass

$\chi_{3,4}^0$ will have insignificant role in the generation of asymmetry and χ_1^0 will play the major role as discussed earlier. However, the evolution of the number density of χ_1^0 will depend on that of χ_2^0 through co-annihilation channel. The ratio of number densities of χ_1, χ_2 with respect to entropy density and the lepton asymmetry with respect to entropy density are defined as

$$Y_{\chi_i} = \frac{n_{\chi_i^0}(z)}{s(z)}; \quad Y_{\Delta L} = \frac{n_l(z) - n_{\bar{l}}(z)}{s(z)}$$

respectively where the entropy density $s(z) = g_* \frac{2\pi^2}{45} \frac{m_{\chi_1}^3}{z^3}$ with the effective number of degrees of freedom $g_* \sim 228$ in R violating MSSM. The coupled Boltzmann equations for $Y_{\chi_1^0}, Y_{\chi_2^0}$ and $Y_{\Delta L}$ are :

$$\frac{dY_{\chi_1^0}(z)}{dz} = -\frac{1}{s(z)H(z)z} \left[\left(\frac{Y_{\chi_1^0}(z)}{Y_{\chi_1^0}^{eq}} - 1 \right) \right.$$
$$\times \left(\gamma_{\chi_1^0}^D + 2(\gamma_{\chi_1^0 l \rightarrow d\bar{u}} + \gamma_{\chi_1^0 \bar{u} \rightarrow l\bar{d}} + \gamma_{\chi_1^0 d \rightarrow lu}) \right)$$
$$\left. + \sum_{i=1}^{2} \left(\frac{Y_{\chi_1^0}(z)}{Y_{\chi_1^0}^{eq}} \frac{Y_{\chi_i^0}(z)}{Y_{\chi_i^0}^{eq}} - 1 \right) \gamma_{\chi_1^0 \chi_i^0 \rightarrow f\bar{f}} \right];$$

$$\frac{dY_{\chi_2^0}(z)}{dz} = -\frac{1}{s(z)H(z)z} \left[\left(\frac{Y_{\chi_2^0}(z)}{Y_{\chi_2^0}^{eq}} - 1 \right) \right.$$
$$\times \left(\gamma_{\chi_2^0}^D + 2(\gamma_{\chi_2^0 l \rightarrow \bar{u}d} + \gamma_{\chi_2^0 \bar{u} \rightarrow l\bar{d}} + \gamma_{\chi_2^0 d \rightarrow lu}) \right)$$
$$+ \sum_{i=1}^{2} \left(\frac{Y_{\chi_2^0}(z)}{Y_{\chi_2^0}^{eq}} \frac{Y_{\chi_i^0}(z)}{Y_{\chi_i^0}^{eq}} - 1 \right) \gamma_{\chi_2^0 \chi_i^0 \rightarrow f\bar{f}}$$
$$\left. + \left(\frac{Y_{\chi_2^0}^2(z)}{Y_{\chi_2^0}^{eq2}} - 1 \right) \gamma_{\chi_2^0 \chi_2^0 \rightarrow W^+ W^-} \right];$$

$$\frac{dY_{\Delta L}(z)}{dz} = \frac{1}{s(z)H(z)z} \left[\epsilon_i \gamma_{\chi_1^0}^D \left(\frac{Y_{\chi_1^0}(z)}{Y_{\chi_1^0}^{eq}} - 1 \right) \right.$$
$$- \sum_{i=1}^{2} \frac{Y_{\Delta L}(z)}{Y_l^{eq}} \left(\frac{1}{2} \gamma_{\chi_i^0}^{LV} + \frac{Y_{\chi_i^0}(z)}{Y_{\chi_i^0}^{eq}} \gamma_{\chi_i^0 l \rightarrow \bar{u}d} \right.$$
$$\left. \left. + \gamma_{\chi_i^0 \bar{u} \rightarrow l\bar{d}} + \gamma_{\chi_i^0 d \rightarrow lu} \right) \right] \quad (5)$$

in which Hubble rate $H(z) = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{m_{\chi_1}^2}{m_{pl} z^2}$ with planck mass $m_{pl} = 1.22 \times 10^{19}$ GeV and other quantities are

$$\gamma_{\chi_1^0}^D = n_{\chi_1^0}^{eq} \frac{K_1(z)}{K_2(z)} \left(\Gamma_{\chi_1^0 \to l u \bar{d}} + \Gamma_{\chi_1^0 \to \bar{l} d \bar{u}} \right.$$

$$\left. + \Gamma_{\chi_1^0 \to \bar{l} l \chi_2^0} + \Gamma_{\chi_1^0 \to q \bar{q} \chi_2^0} \right)$$

$$\gamma_{\chi_2^0}^D = n_{\chi_2^0}^{eq} \frac{K_1(z)}{K_2(z)}$$

$$\times \left(\Gamma_{\chi_2^0 \to l u \bar{d}} + \Gamma_{\chi_2^0 \to \bar{l} d \bar{u}} \right) = \gamma_{\chi_2^0}^{LV};$$

$$\gamma_{\chi_1^0}^{LV} = n_{\chi_1^0}^{eq} \frac{K_1(z)}{K_2(z)} \left(\Gamma_{\chi_1^0 \to l u \bar{d}} + \Gamma_{\chi_1^0 \to \bar{l} d \bar{u}} \right);$$

$$\gamma_{\psi_1 \psi_2 \to \phi_1 \phi_2} = \frac{m_{\chi_2^0}}{64\pi^4 z} \times \int_{s_{min}}^{\infty} ds \frac{2\lambda(s, m_{\psi_1}^2, m_{\psi_2}^2)}{s} \sigma(s) \sqrt{s} K_1 \left(\frac{\sqrt{s} z}{m_{\chi_2^0}} \right);$$

$$s_{min} = max \left[(m_{\psi_1} + m_{\psi_2})^2, (m_{\phi_1} + m_{\phi_2})^2 \right].$$

In first two Boltzman equations f corresponds to leptons and quarks. $K_i(z)$ are usual modified Bessel Functions and different thermally averaged decays are defined as $\gamma_{\chi_2^0}^D, \gamma_{\chi_1^0}^D$, and L violating $\gamma_{\chi_1^0}^{LV}$ and $\gamma_{\chi_2^0}^{LV}$ and different thermally averaged scattering cross-sections are defined as $\gamma_{\psi_i \psi_j \to \phi_1 \phi_2}$ with $i, j = 1, 2$ and ϵ is the CP asymmetry parameter as mentioned in Eq. (3). The superscript eq denotes the corresponding values in thermal equilibrium. Unlike $\gamma_{\chi_2^0}^D$, the $\gamma_{\chi_1^0}^D$ has L conserving decay term also and unlike χ_1^0, the χ_2^0 has annihilation to $W^+ W^-$ also. Both L conserving and L violating scatterings are considered in first two Boltzman equations as they reduce $n_{\chi_i^0}$ while L violating scatterings are considered in the last Boltzman equation. The thermally averaged γ corresponding to various scatterings processes, their conjugate and inverse processes are same and not written separately but associated factors with γ have been taken appropriately in Boltzman equations.

In presence of sphalerons the leptonic asymmetry $Y_{\Delta L}$ will be converted to baryonic asymmetry $Y_{\Delta B}$ as [44,45]

$$Y_{\Delta B} = \frac{n_B(z) - n_{\bar{B}}(z)}{s(z)} = -\left(\frac{8N_f + 4N_H}{22N_f + 13N_H} \right) Y_{\Delta L}$$

where $N_f = 3$ is the number of lepton generations and $N_H = 2$ is the number of Higgs doublets in the R-parity violating MSSM.

Based on recent experimental data [1,2] the observed baryonic asymmetry corresponds to $Y_{\Delta B} \approx 10^{-11}$ at recombination. In Fig. 3, we have shown the evolution of the baryonic asymmetry $Y_{\Delta B}$ with temperature ($z = m_{\chi_1}/T$) after numerically solving above Boltzmann equations. The required $Y_{\Delta B}$ could be obtained around $z \sim 30$ at leptogenesis scale and to get $Y_{\Delta B}$ at recombination, the $Y_{\Delta B}$ at leptogenesis scale shown in Fig. 3 is to be divided by the additional entropy dilution factor $f \approx 30$ [3]. For numerical analysis, all left and right squark and all left and right slepton masses have been assumed to be equal. We have considered different sets of benchmark points in Tables 1 and 2. In Table 1, we have considered slepton and squark

masses to be equal and such equal mass has been denoted as $m_{\tilde{f}}$. In Table 1, for all sets, the phase $\phi = \pi/4$ has been considered for which lepton asymmetry is maximal as it is proportional to $\sin 2\phi$. However, in Table 2, we have considered different slepton and squark masses and also different phases in different sets of benchmark points. Figure 3a–c correspond to benchmark points in Table 1 and Fig. 3d, e correspond to benchmark points in Table 2. Choice of λ' in all cases satisfies phenomenological constraint [36–42] for heavy sfermion masses considered here. $|\mu|$ parameter is required to be higher than the two masses of lighter two neutralinos as discussed earlier. We will consider its specific choice later in our discussion for neutrino mass. As one can see in the last term of the 3rd Boltzman equations, there are particularly three different scattering processes mentioned whose inverse also has been taken into account with appropriate pre-factors – which could play some role in washing out or increasing the asymmetry. The first one depends on slepton mass and the other two depends on squark masses. To study the role of such terms in generating asymmetry we have considered same as well as different choices of slepton and squark masses in Tables 1 and 2.

The required minimum freeze out temperature is $T_{\text{out}} \sim 200$ GeV for sphaleron to convert leptonic asymmetry to baryonic asymmetry [25,46–48] for weakly first order or second order phase transition. We do not need here strictly first order phase transition. So the leptonic asymmetry can be successfully converted to baryonic asymmetry by the sphalerons for freeze out temperature $T \gtrsim 200$ GeV for which $z \lesssim 30$ depending on our choices of m_{χ_1} in Tables 1 and 2. If this condition is not satisfied in any plot in Fig. 3, we have to discard that for successful generation of baryonic asymmetry. This is because the conversion of leptonic asymmetry to baryonic asymmetry will be actually very less than that shown in the figure as the relation between these two asymmetries as mentioned earlier through sphaleron transition will not be valid. As for example, in the plot labelled as BP8 in Fig. 3b, the required baryonic asymmetry seems to be obtained but freeze-out occurs at $z \sim 40$ and this means the freeze out temperature is below 200 GeV. So we have to discard set of benchmark points in BP8 for successful generation of baryonic asymmetry. From Fig. 3a–c, it is found that for benchmark points BP1, BP2, BP5, BP6, BP7, the successful baryonic asymmetry could be obtained. However, for BP2 and BP5, the above condition is narrowly satisfied as $z \lesssim 25$ is expected for freeze out for $m_{\chi_1} = 5$ TeV. So the lightest neutralino mass m_{χ_2} could be about 5 GeV and sfermion mass about 7 GeV as seen in BP6. If m_{χ_2} is considered futher lower at about 4 GeV, then the sfermion mass could be higher than 30 TeV or so as seen in plots BP1 and BP2. In this case, for lower sfermion mass, the required asymmetry is not obtained as can be seen in other plots in Fig. 3a–c. In Fig. 3d, plots BP11, BP12, BP13 and BP14 sat-
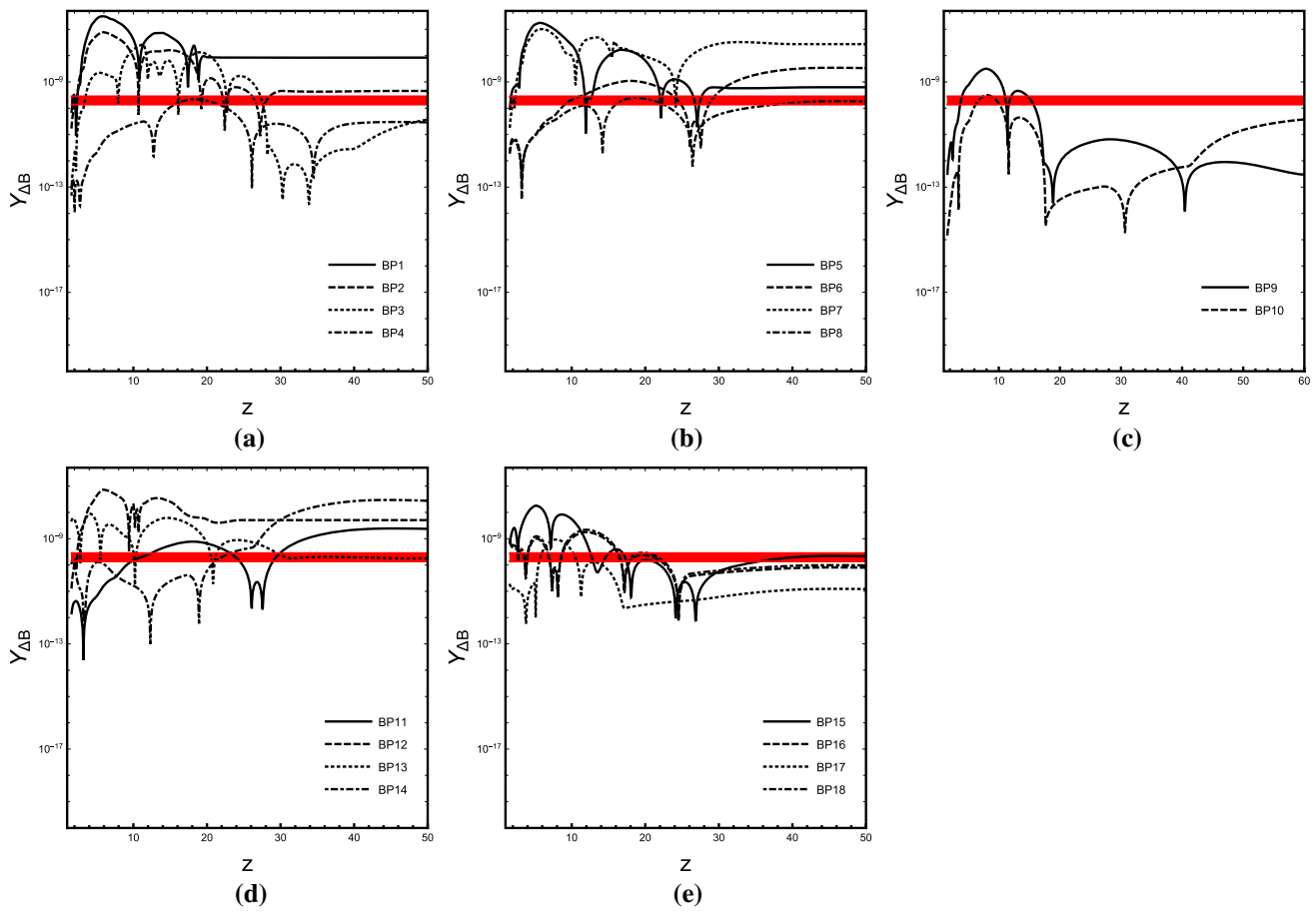
Fig. 3 Plot of $Y_{\Delta B}$ versus $z = m_\chi / T$ shown in **a**–**c** with phase $\phi = \pi/4$ for different sets of benchmark points as shown in Table 1. Plot shown in **d** and **e** for different sets of benchmark points as shown in Table 2. The red horizontal line corresponds to required approximate baryonic asymmetry

Table 1 Different benchmark points considered for different plots in Fig. 3a–c. For all these sets $\phi = \pi/4$

	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10
m_{χ_1}	5 TeV	5 TeV	5 TeV	5 TeV	5 TeV	6 TeV	6 TeV	6 TeV	3 TeV	3 TeV
m_{χ_2}	4 TeV	4 TeV	4 TeV	4 TeV	3.5 TeV	5 TeV	5 TeV	4 TeV	2 TeV	1.5 TeV
λ'	0.01	0.01	0.01	0.1	0.01	0.01	0.01	0.01	0.01	0.01
$m_{\tilde{f}}$	60 TeV	30 TeV	7 TeV	6 TeV	60 TeV	7 TeV	30 TeV	7 TeV	5 TeV	4 TeV

Table 2 Different benchmark points considered for different plots in Fig. 3d, e

	BP11	BP12	BP13	BP14	BP15	BP16	BP17	BP18
m_{χ_1}	6 TeV	6 TeV	5 TeV	5 TeV	6 TeV	5 TeV	5 TeV	5 TeV
m_{χ_2}	5 TeV	5 TeV	4 TeV	4 TeV	5 TeV	4 TeV	4 TeV	4 TeV
λ'	0.01	0.01	0.01	0.01	0.01	0.1	0.1	0.1
$m_{\tilde{q}}$	7 TeV	30TeV	30 TeV	6 TeV	20 TeV	30 TeV	6 TeV	30 TeV
$m_{\tilde{l}}$	7 TeV	30 TeV	6 TeV	30 TeV	7 TeV	6 TeV	30 TeV	6 TeV
ϕ	$\pi/8$	$\pi/8$	$\pi/4$	$\pi/4$	$\pi/8$	$\pi/8$	$\pi/8$	$\pi/6$

isfy the required freeze out value of z and may be considered for the generation of required baryonic asymmetry. But in Fig. 3e, all the plots are not suitable for the generation of baryonic asymmetry due to lower than 200 GeV freeze out

temperature with corresponding higher z value. Plots BP11 and BP12 have the same benchmark points like BP6 and BP7 respectively except the phase which is $\pi/8$. There is no significant change due to that. However, plots in BP13 and

BP14 are somewhat interesting. In BP13, the squark mass is heavier and in that case, for lighter slepton mass at 6 TeV, the required baryonic asymmetry is obtained. In BP14, the slepton mass is heavier and in that case, for lighter squark mass at 6 TeV, the required baryonic asymmetry is obtained. In both BP13 and BP14, the lightest neutralino mass is at 4 GeV. In Fig. 3e, particularly in case of BP15, with light slepton but squark mass at 20 TeV, required asymmetry is not produced. From earllier plots in Fig. 3d, it seems further higher squark mass like 30 TeV or further lower like 7 TeV could work. In case of BP16, BP17 and BP18, we have considered higher value of L violating coupling, in comparison to other sets of benchmark points and required baryonic asymmetry is not obtained. So from Fig. 3, it is seen that for successful leptogenesis at low energy scale around TeV, the allowed parameter space of sfermion masses and neutralino masses get constrained from the requirement of conversion of leptonic asymmetry to baryonic asymmetry through sphaleron transition. From different plots, one can see that with appropriate combination of other parameters, the successful baryonic asymmetry could be possible for (1) lightest neutralino mass as low as 4 TeV (2) slepton or squark mass as low as 6 TeV for which either squark or slepton is required to be heavier around 30 TeV (3) equal squark and slepton mass as low as 7 TeV.

The same L violating λ' coupling considered for leptogenesis could also give Majorana neutrino mass. It can be obtained from one loop Feynman diagram with left and right d-squark and d-quark (with left-right mixing) in the loop with L violating coupling. Instead of see-saw mechanism here smallness of neutrino mass occurs due to one loop diagram. Neutrino mass matrix elements can be written as [49–52]

$$m_{\nu_{ij}} \approx \sum_{k,l} \frac{3\lambda'_{ikl}\lambda'_{jlk}m_k m_l \widetilde{m}}{16\pi^2 \widetilde{m}_q^2} \tag{6}$$

where m_k and m_l are the masses of d-quarks and $\widetilde{m} \sim (A, \mu)$ corresponds to SUSY breaking parameters and $\widetilde{m}_q$ is the d-squark masses. Main contribution is expected to come from b-quark mass in the numerator. Considering one of the $\lambda' \sim 10^{-2}$ corresponding to Fig. 3 (for which successful baryonic asymmetry has been obtained) and other λ' couplings lesser than that and $\widetilde{m} = 20$TeV; $\widetilde{m}_q = 30$ TeV and $k = l = b$ one can easily satisfy the cosmological bound $\sum m_{\nu_i} \lesssim 0.1$ eV [53]. Considering $\lambda' \sim 10^{-2}$ is appropriate to get mass square differences of about 2×10^{-3}eV^2 to satisfy atmospheric neutrino oscillation data [54]. For other L violating couplings like λ'_{1jk}, λ'_{2jk} lesser than λ' it is possible to

get mass square differences of about 7×10^{-5} satisfying solar neutrino oscillation data [54]. If we consider lighter squark mass about 6 TeV as follows from Figure 3d, then to get similar order of neutrino mass with one λ' value as 10^{-2} like before and other λ' couplings lesser than that, we may consider either k or l to correspond to d quark instead of b quark, then it could be possible to satisfy required neutrino masses square differences and the cosmological bound on neutrino masses. However, alternate option of reducing $\widetilde{m}$ to about 1 TeV is not possible in our mechanism of generating baryonic asymmetry because that would violate our requirement of gaugino mass condition mentioned after Eq. (2).

4 Conclusion

The lighter two neutralinos are mostly gauginos after symmetry breaking at the electro-weak scale. This could be envisioned in Supergravity models with symmetry broken in the hidden sector [55–59]. At LHC there is scope to verify the possibility of such leptogenesis mechanism for which there could be pair production of such gauginos followed by decay of next to lightest neutralino to the lightest one by L conserving decay mode and the lightest and next to lightest one by L violating decay mode as mentioned earlier giving multi-lepton signature. Particularly, the case of either slepton or squark mass as light as 6 TeV is possible in the plots in Fig. 3d. In that case, their pair production may be possible at LHC in near future. However, in several sets of benchmark points, the sfermion masses are found to be heavier. Such heavy masses are consistent [60] with the kind of Higgs mass observed at LHC. Besides, because of sfermion masses in few TeV scale or more, it is difficult to constrain Majorana phases [61,62] even after recent improvement on the experimental bound of electric dipole moment of particularly electron [63]. So the phase $\phi = \pi/4$ as considered in our numerical analysis, is easily allowed. However, following various cases considered in Fig. 3 it seems that the lightest supersymmetric particle – the lightest neutralino in MSSM scenario should have mass not lower than about 4 TeV.

In this scenario in $\rlap{/}{R}$ MSSM with gaugino mass conditions, baryonic asymmetry could be sufficient without any fine tuning of model parameters because leptogenesis is possible with one L violating coupling and CP violation due to Majorana phase could be maximal.

Appendix A: Details of asymmetry

Here we present the detailed expression for the asymmetry given in eq.(3) related to leptonic asymmetry. The asymmetry ϵ can be rewritten as:

$$\epsilon = \frac{\Gamma_{\chi_1^0 \to ul\bar{d}} - \Gamma_{\chi_1^0 \to \bar{u}d\bar{l}}}{\Gamma_{\chi_1^0 \to lu\bar{d}} + \Gamma_{\chi_1^0 \to \bar{l}d\bar{u}}} + \Gamma_{\chi_1^0 \to l\bar{l}\chi_2^0} + \Gamma_{\chi_1^0 \to q\bar{q}\chi_2^0} = \frac{\Gamma_\delta}{\Gamma_{tot}}$$

(A1)

where the numerator is given as:

$$\Gamma_\delta = \Gamma_{\chi_1^0 \to ul\bar{d}} - \Gamma_{\chi_1^0 \to \bar{u}d\bar{l}}$$

$$= \int_{z_{l_-}}^{z_{l_+}} \int_{z_{u_-}}^{z_{u_+}} \frac{3m_{\chi_1}}{256\pi^3} \left(\frac{1}{2} \sum_{\text{spins}} |\delta|^2 \right) dz_l dz_d$$

(A2)

in which $z_{l_-} = 2r_l z_{l_+} = 1 + r_l^2 - (r_u + r_{\bar{d}})^2$; $r_i = m_i/m_{\chi_1^0}$; $z_f = 2p_{\chi_1^0} \cdot p_f/(m_{\chi_1^0}^2) = 2E_f/m_{\chi_1^0}$ and $(z_u)_\pm = \frac{1}{2(1-z_l+r_l^2)}[(2-z_l)(1+r_l^2+r_u^2-r_{\bar{d}}^2-z_l) \pm \sqrt{z_l^2-4r_l^2} \Lambda^{1/2}(1+r_l^2-z_l, r_u^2, r_{\bar{d}}^2)]$ in which $\Lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$ $z_{\bar{d}} = 2 - z_u - z_l$. $|\delta|^2$ in Γ_δ is given by

$$|\delta|^2 = -4r_{\chi_2^0} \lambda_{lud}'^2 \sin 2\phi g^2 g'^2$$

$$\left[\Im[\tilde{C}_1^l] \left(\frac{1}{4} \frac{z_l(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_l^2-z_l-r_{\bar{l}}^2)^2} \right.\right.$$

$$+ \frac{1}{6} \frac{r_l^2(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_u^2-r_{\bar{u}}^2-z_u)(1+r_l^2-r_{\bar{l}}^2-z_l)}$$

$$+ \frac{1}{6} \frac{z_u(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)-z_{\bar{d}}(1+r_{\bar{d}}^2-r_u^2-r_l^2-z_{\bar{d}})+z_l(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_u^2-r_{\bar{u}}^2-z_u)(1+r_l^2-r_{\bar{l}}^2-z_l)}$$

$$+ \left.\frac{1}{3} \frac{z_{\bar{d}}(1+r_{\bar{d}}^2-r_u^2-r_l^2-z_{\bar{d}})-z_u(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)+z_l(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_u^2-r_{\bar{u}}^2-z_u)(1+r_{\bar{d}}^2-r_{\bar{d}}^2-z_{\bar{d}})} \right)$$

$$+ \Im[\tilde{C}_2^l] \left(\frac{1}{2} \frac{r_l^2(1+r_l^2+r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_l^2-z_l-r_{\bar{l}}^2)^2} + \frac{1}{3} \frac{r_l^2(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_l^2-z_l-r_{\bar{l}}^2)(1+r_{\bar{d}}^2-r_{\bar{d}}^2-z_{\bar{d}})} \right)$$

$$+ \Im[\tilde{C}_1^u] \left(\frac{1}{18} \frac{z_u(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)-z_{\bar{d}}(1+r_{\bar{d}}^2-r_u^2-r_l^2-z_{\bar{d}})+z_l(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)}{(1+r_l^2-z_l-r_{\bar{l}}^2)(1+r_u^2-z_u-r_{\bar{u}}^2)} \right.$$

$$- \frac{1}{108} \frac{z_u(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)}{(1+r_l^2-r_{\bar{l}}^2-z_l)(1+r_{\bar{d}}^2-r_{\bar{r}}^2-z_{\bar{d}})}$$

$$+ \left.\frac{1}{27} \frac{z_{\bar{d}}(1+r_{\bar{d}}^2-r_u^2-r_l^2-z_{\bar{d}})-z_l(1+r_l^2-r_u^2-r_{\bar{d}}^2-z_l)+z_u(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u))}{(1+r_u^2-r_{\bar{u}}^2-z_u)(1+r_{\bar{d}}^2-r_{\bar{d}}^2-z_{\bar{d}})} \right)$$

$$+ \left.\Im[\tilde{C}_2^u] \left(\frac{1}{18} \frac{r_u^2(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)}{(1+r_l^2-r_{\bar{u}}^2-z_l)(1+r_u^2-r_{\bar{u}}^2-z_u)} + \frac{1}{27} \frac{r_u^2(1+r_u^2-r_l^2-r_{\bar{d}}^2-z_u)}{(1+r_u^2-r_{\bar{u}}^2-z_u)(1+r_{\bar{d}}^2-r_{\bar{d}}^2-z_{\bar{d}})} \right) \right]$$

(A3)

in which

$$\tilde{C}_1^f = \frac{1}{(4r_f^2 - 2z_f)} \times \left[2r_f^2 \left(\mathcal{B}_0(m_f^2, m_{\tilde{f}}^2, m_{\chi_2^0}^2) - \mathcal{B}_0(m_{\chi_1^0}^2\right.\right.$$

$$+ m_f^2 - m_{\chi_1^0}^2 z_f, m_{\chi_2^0}^2, m_f^2)$$

$$+ (m_f^2 - m_{\tilde{f}}^2)\mathcal{C}_0(m_{\chi_1^0}^2, m_f^2, \frac{1}{2}m_{\chi_1^0}^2 z_f, m_{\tilde{f}}^2, m_f^2, m_{\chi_2^0}^2)\Big)$$

$$- z_f \left(\mathcal{B}_0(m_{\chi_2^0}^2, m_{\tilde{f}}^2, m_f^2) - \mathcal{B}_0(m_{\chi_1^0}^2 + m_f^2 - m_{\chi_1^0}^2 z_f, m_{\chi_2^0}^2, m_{\tilde{f}}^2)\right.$$

$$+ (m_{\chi_2^0}^2 - m_{\tilde{f}}^2)\mathcal{C}_0(m_{\chi_1^0}^2, m_f^2, \Big)\right];$$

$$\frac{1}{2}m_{\chi_1^0}^2 z_f, m_{\tilde{f}}^2, m_f^2, m_{\chi_2^0}^2)\tilde{C}_2^f = \frac{1}{(4r_f^2 - 2z_f)}$$

$$\times \left[2r_f^2 \left(\mathcal{B}_0(m_{\chi_1^0}^2, m_{\tilde{f}}^2, m_f^2) - \mathcal{B}_0(m_{\chi_1^0}^2\right.\right.$$

$$+ m_f^2 - m_{\chi_1^0}^2 z_f, m_{\chi_2^0}^2, m_{\tilde{f}}^2)$$

$$+ (m_{\chi_2^0}^2 - m_{\tilde{f}}^2)\mathcal{C}_0(m_{\chi_1^0}^2, m_f^2, \frac{1}{2}m_{\chi_1^0}^2 z_f, m_{\tilde{f}}^2, m_f^2, m_{\chi_2^0}^2)\Big)$$

$$- z_f \left(\mathcal{B}_0(m_f^2, m_{\tilde{f}}^2, m_{\chi_2^0}^2) - \mathcal{B}_0(m_{\chi_1^0}^2\right.$$

$$\mathcal{C}_0(p_1^2, p_2^2, p_1.p_2, m_1^2, m_2^2, m_3^2)$$

$$= \int \frac{dl^4}{(2\pi)^4} \frac{1}{(l^2 - m_1^2)((l + p_1)^2 - m_2^2)((l + p_2)^2 - m_3^2)}.$$

The denominator of Eq. (3) is given as:

$$\Gamma_{tot} = \Gamma_{\chi_1^0 \to lu\bar{d}} + \Gamma_{\chi_1^0 \to \bar{l}d\bar{u}} + \Gamma_{\chi_1^0 \to l\bar{l}\chi_2^0} + \Gamma_{\chi_1^0 \to q\bar{q}\chi_2^0} \quad \text{(A4)}$$

in which

$$\Gamma_{\chi_1^0 \to lu\bar{d}} + \Gamma_{\chi_1^0 \to \bar{l}d\bar{u}}$$

$$= \int_{z_{l_-}}^{z_{l_+}} \int_{z_{u_-}}^{z_{u_+}} \frac{6m_{\chi_1}}{256\pi^3} \left(\frac{1}{2}\sum_{\text{spins}} |\mathcal{M}_+|^2\right) dz_l dz_d \quad \text{(A5)}$$

in which $z_{l_-} = 2r_l$; $z_{l_+} = 1 + r_l^2 - (r_u + r_{\bar{d}})^2$; $z_f = 2p_{\chi_1^0}.p_f/(m_{\chi_1^0}^2) = 2E_f/m_{\chi_1^0}$ and $(z_u)_\pm = \frac{1}{2(1 - z_l + r_l^2)}$
$\left[(2 - z_l)(1 + r_l^2 + r_u^2 - r_{\bar{d}}^2 - z_l) \pm \sqrt{z_l^2 - 4r_l^2}\Lambda^{1/2}(1 + r_l^2 - z_l, r_u^2, r_{\bar{d}}^2)\right]$.

$$|\mathcal{M}_+|^2 = \lambda_{uld}'^2 g'^2 \left(z_l(1 + r_l^2 - r_u^2 - r_{\bar{d}}^2 - r_{\bar{d}}^2 - z_l)\right.$$

$$\left[\frac{1}{2(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)^2} + \frac{1}{6(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)}\right.$$

$$\left. + \frac{1}{3(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)(1 + r_{\bar{d}}^2 - r_{\tilde{d}}^2 - z_{\bar{d}})}\right]$$

$$+ z_u(1 + r_u^2 - r_l^2 - r_{\bar{d}}^2 - z_u)\left[\frac{1}{18(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)^2} + \frac{1}{6(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)}\right.$$

$$\left. + \frac{1}{3(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)(1 + r_{\bar{d}}^2 - r_{\tilde{d}}^2 - z_{\bar{d}})} - \frac{1}{9(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)(1 + r_{\bar{d}}^2 - r_{\tilde{d}}^2 - z_{\bar{d}})}\right]$$

$$+ z_{\bar{d}}(1 + r_{\bar{d}}^2 - r_u^2 - r_l^2 - z_{\bar{d}})\left[\frac{2}{9(1 + r_{\bar{d}}^2 - r_{\tilde{r}}^2 - z_{\bar{d}})^2} - \frac{1}{6(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)}\right.$$

$$\left.\left. + \frac{1}{3(1 + r_l^2 - r_{\tilde{l}}^2 - z_l)(1 + r_{\bar{d}}^2 - r_{\tilde{d}}^2 - z_{\bar{d}})} + \frac{1}{9(1 + r_u^2 - r_{\tilde{u}}^2 - z_u)(1 + r_{\bar{d}}^2 - r_{\tilde{d}}^2 - z_{\bar{d}})}\right]\right) \quad \text{(A6)}$$

and

$$+ m_f^2 - m_{\chi_1^0}^2 z_f, m_{\chi_2^0}^2, m_f^2)$$

$$+ (m_f^2 - m_{\tilde{f}}^2)\mathcal{C}_0(m_{\chi_1^0}^2, m_f^2, \frac{1}{2}m_{\chi_1^0}^2 z_f, m_{\tilde{f}}^2, m_f^2, m_{\chi_2^0}^2)\Big)\ ];$$

$$\mathcal{B}_0(p^2, m_1^2, m_2^2) = \int \frac{dl^4}{(2\pi)^4} \frac{1}{(l^2 - m_1^2)((l + p)^2 - m_2^2)};$$

$$\Gamma_{\chi_1^0 \to f\bar{f}\chi_2^0}$$

$$= \int_{z_{1_-}}^{z_{1_+}} \int_{z_{2_-}}^{z_{2_+}} \frac{m_{\chi_1}}{256\pi^3} \left(\frac{1}{2}\sum_{\text{spins}} |\mathcal{M}|^2\right) dz_1 dz_2 \quad \text{(A7)}$$

in which $z_{1_-} = 2r_f$; $z_{1_+} = 1 + r_f^2 - (r_f + r_{\chi_2^0})^2$; $z_{1(2)} = 2p_{\chi_1^0} \cdot p_{f(\bar{f})}/(m_{\chi_1^0}^2) = 2E_{f(\bar{f})}/m_{\chi_1^0}$ and $(z_2)_\pm = \frac{1}{2(1-z_1+r_f^2)}$

$$\left[(2-z_1)(1 + 2r_f^2 - r_{\chi_2^0}^2 - z_1) \pm \sqrt{z_1^2 - 4r_f^2} \Lambda^{1/2}(1 + r_f^2 - z_1, r_f^2, r_{\chi_2^0}^2) \right];$$

$$|\mathcal{M}|^2 = N_c^f 4g^2 g'^2 T_3^{f^2} (Q_f - T_3^f)^2 \left[\frac{z_1(1 - r_{\chi_2^0}^2 - z_1)}{(1 + r_f^2 - r_{\bar{f}}^2 - z_1)^2} \right.$$
$$\left. + \frac{z_2(1 - r_{\chi_2^0}^2 - z_2)}{(1 + r_f^2 - r_{\bar{f}}^2 - z_2)^2} \frac{r_{\chi_2^0}(r_{\chi_2^0}^2 - 2r_f^2 + z_1 + z_2 - 1)}{(1 + r_f^2 - r_{\bar{f}}^2 - z_1)(1 + r_f^2 - r_{\bar{f}}^2 - z_2)} \right]$$

where the factor N_c^f (equal to 1 for leptons and 3 for quarks) is for the sum over colors and Q_f is the electric charge of the fermion (i.e for charged leptons $Q_l = -1$) and $T_3^f = 1/2$ for $f = u, \nu$ and $T_3^f = -1/2$ for $f = d, l$. In Fig. 1, there are three diagrams at the tree level and two diagrams at the loop level. For brevity, the decay width of χ_1^0 has been shown for one tree level diagram with $\tilde{l}$ in the propagator and Γ_δ has been shown for the interference of one tree diagram and one loop diagram with $\tilde{l}$ in the propagators. For $\tilde{u}$ and $\tilde{d}$ in the propagators one will get similar expressions with the appropriate replacement of $\tilde{l}$ by $\tilde{u}$ or $\tilde{d}$ by their masses and appropriate couplings. For equal slepton and squark mass, all these diagrams will give Γ_δ approximately 6 times than what is shown and the decay width of χ_1^0 will be around 9 times than what is shown.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: This is a theoretical paper and this manuscript has no associated data. All the required data is already provided by the authors.]

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