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Neutrino masses, baryogenesis and bilinear R-parity violation

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Abstract

We consider the impact of cosmological B–L constraints on supersymmetric standard models without R-parity which can account for the observed atmospheric and solar neutrino masses and mixing. In order to avoid erasing any primordial baryon or lepton asymmetry above the electroweak scale, B–L violation for at least one generation should be sufficiently small. We show that a narrow parameter space of the bilinear model may satisfy such constraints as well as provide the form of the neutrino mass matrix required by current data.

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1. Introduction

In recent years the increasing evidence for neutrino oscillations from various experiments [1] has led to the active study of R-parity violating extensions of the minimal supersymmetric standard model (MSSM) [2]. Such models maintain the particle spectrum of the MSSM but contain renormalizable lepton flavour violating couplings with which the observed neutrino oscillations and mass differences [3] can be accommodated [4,5]. The atmospheric neutrino data is explained by oscillations $\nu_\mu \to \nu_\tau$, and a global analysis gives the following 3σ ranges [6]

$$0.3 \leqslant \sin^2\theta_{\rm atm} \leqslant 0.7,$$
$$1.2 \times 10^{-3}\ {\rm eV}^2 \leqslant \Delta m^2_{\rm atm} \leqslant 4.8 \times 10^{-3}\ {\rm eV}^2 \qquad (1)$$

with maximal mixing $\sin^2\theta_{\rm atm} = 0.5$ and $\Delta m^2_{\rm atm} = 2.5 \times 10^{-3}$ eV^2 as the best fit point. Similarly, the solar neutrino data is explained by ν_e oscillation into a mixture of ν_μ and ν_τ. Global analyses suggest a large mixing angle and a much smaller mass squared difference. At 3σ we have [6,7]

$$0.29 \leqslant \tan^2\theta_{\rm sol} \leqslant 0.86,$$
$$5.1 \times 10^{-5}\ {\rm eV}^2 \leqslant \Delta m^2_{\rm sol} \leqslant 9.7 \times 10^{-5}\ {\rm eV}^2 \qquad (2)$$

with $\tan^2\theta_{\rm sol} = 0.46$ and $\Delta m^2_{\rm sol} = 6.9 \times 10^{-5}$ eV^2 as the best fit point.

In the R-parity violating MSSM, the lightest supersymmetric particle is unstable and decays in the detector with branching ratios which are correlated with

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the neutrino mixing [8]. This provides a robust, experimentally accessible test of the model at the large hadron collider and/or a e^+e^- linear collider [9]. Bilinear R-parity violation (BRpV) is the minimal extension of the MSSM with R-parity violating terms [4,10–13]. In the BRpV model, the usual universality condition of the soft SUSY breaking terms must be relaxed in order to accommodate the observed bi-large mixing [14–17]. Another option for obtaining a realistic neutrino mass matrix is to allow both bilinear and trilinear couplings while keeping the universality condition. The minimal model of trilinear R-parity violation (TRpV) assumes the dominance of the third generation trilinear couplings and thus contains five free parameters of lepton number violation which are able to fit all the neutrino data successfully [5].

In connection with neutrino physics, there appears an important cosmological consideration. As is well known, the see-saw mechanism provides a natural way to generate the baryon asymmetry of the universe through the out-of-equilibrium decay of a heavy right-handed neutrino [18]. Being a new physics model just around TeV scale, the R-parity violating MSSM can hardly accommodate such a mechanism of baryogenesis. However, in the MSSM, the so-called Affleck–Dine mechanism can successfully work to generate the required amount of the baryon asymmetry in the flat direction along, e.g., LH_u [19]. It is notable that such a property is unaltered even with the presence of R-parity violating terms which must be very small to generate tiny neutrino masses.

In this Letter we are not concerned with explaining the baryon asymmetry but instead assume that a B–L asymmetry was generated primordially by some means at a high temperature. Our intention is its preservation at all energies down to the electroweak scale when the sphalerons finally fall out of equilibrium. Lepton number violating couplings introduced around the TeV scale are capable of erasing any pre-existing baryon/lepton asymmetry in the universe together with $B + L$ violating sphaleron processes [20–22]. This is often raised as a deficiency of R-parity violating models. The purpose of this Letter is to explicitly check if such cosmological constraints on the R-parity and lepton number violating couplings can be satisfied while simultaneously accommodating the form of the neutrino mass matrix indicated by the atmospheric, solar and reactor neutrino experiments. We will see that TRpV can be ruled out in this spirit. The cosmological bounds in BRpV have been considered in a previous qualitative study [23]. We develop their analysis and apply the bounds to the currently favoured bi-large mixing form of the neutrino mass matrix. We will show that the cosmological B–L constraints strongly restrict the parameter space of good solutions for the neutrino mass matrix and thus only a narrow parameter space can survive. Thus our study constitutes an existence proof of the compatibility of BRpV with the preservation of a primoridially generated B–L asymmetry.

2. Neutrino masses from R-parity violation

We briefly summarize the mechanism of generating neutrino mass and mixing by R-parity violating couplings, both bilinear and trilinear, and discuss their sizes to explain the atmospheric and solar neutrino oscillations. The R-parity violating MSSM predicts a hierarchical neutrino mass spectrum. The atmospheric mass scale corresponds approximately to the heaviest neutrino mass, m_3, and it is generated at tree level via a low energy see-saw mechanism due to the mixing of the neutrinos with the neutralinos. On the other hand, the solar mass scale, corresponds approximately to the second heaviest neutrino, m_2, and is generated at the one loop level. The atmospheric neutrino mixing is also predicted by tree level physics, and depends in a simple way on sneutrino vacuum expectation values expressed in the basis where the bilinear parameters are removed from the superpotential. On the other hand, the solar neutrino mixing angle is again predicted by one-loop physics which is mainly determined either by the trilinear couplings in the superpotential or by the bilinear parameters in the scalar potential. Let us remark, however, that we cannot exclude the possibility of the loop mass dominating over the tree mass, which may have an interesting implication for baryogenesis as will be discussed later.

TRpV: in the TRpV model with the universality condition of the soft terms, one introduces the trilinear R-parity violating couplings in the superpotential as follows

$$W = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k. \tag{3}$$

In this scheme, the bilinear term $L_i H_2$ in the superpotential can be rotated away to the above trilinear terms at an ultraviolet scale. However, non-vanishing bilinear terms appear at the weak scale which will be discussed below. Here, we concentrate on the one-loop neutrino mass whose main contribution takes the form

$$M_{ij}^{\text{loop}} = 3\frac{\lambda'_{i33}\lambda'_{j33}}{8\pi^2}\frac{m_b^2(A_b+\mu\tan\beta)}{m^2_{\tilde b_1}-m^2_{\tilde b_2}}\ln\frac{m^2_{\tilde b_1}}{m^2_{\tilde b_2}} + \frac{\lambda_{i33}\lambda_{j33}}{8\pi^2}\frac{m_\tau^2(A_\tau+\mu\tan\beta)}{m^2_{\tilde\tau_1}-m^2_{\tilde\tau_2}}\ln\frac{m^2_{\tilde\tau_1}}{m^2_{\tilde\tau_2}}. \tag{4}$$

Note that we have picked up λ'_{i33} and λ_{i33} which give the largest contribution to the neutrino mass under the assumption that all the couplings are of a similar magnitude. Typically, the solar neutrino mass and mixing is determined by the second term of Eq. (4) and thus we can have a rough estimate of the required sizes of λ_{i33} as follows

$$\lambda_{133} \sim \lambda_{233} \approx 8\times 10^{-5}\left(\frac{\tilde m}{300\ \text{GeV}}\right)^{1/2}\left(\frac{m_2}{8\ \text{MeV}}\right)^{1/2}, \tag{5}$$

where we take $\tilde m = A_\tau + \mu\tan\beta = m_{\tilde\tau_{1,2}}$ and $m_2 \approx \sqrt{\Delta m^2_{\text{sol}}}$. Indeed, detailed analysis shows that one needs the trilinear couplings $\lambda'_{233,333} \sim \lambda_{133,233} \sim \mathcal{O}(10^{-5})$ to accommodate the required bi-large mixing of the atmospheric and solar neutrino oscillations [5]. In the next section, we will see that such values are far above the baryogenesis constraints.

BRpV: forbidding the lepton number violating trilinear couplings in the superpotential (3), the BRpV model allows the following dimension-two terms,

$$W = \mu(\epsilon_i L_i H_2 + H_1 H_2),$$
$$V_{\text{soft}} = \mu(\epsilon_i B_i L_i H_2 + B H_1 H_2) + m^2_{L_iH_1} L_i H_1^\dagger + \text{h.c.}, \tag{6}$$

in the superpotential and in the soft supersymmetry breaking scalar potential, respectively. Here we have used the same notation for the superfields and their scalar components. The tree-level neutrino mass matrix arising from the above bilinear parameters can be written as follows

$$M_{ij}^{\text{tree}} = \frac{M_Z^2}{F_N}\xi_i\xi_j c_\beta^2, \tag{7}$$

where $F_N \equiv M_1M_2/(c_W^2 M_1 + s_W^2 M_2) + M_Z^2 c_{2\beta}/\mu$ and $\xi_i \equiv \langle\tilde\nu_i\rangle/\langle H_1\rangle - \epsilon_i$ [14]. Recall that ξ_i results from the non-universality of soft terms between L_i and H_1 as follows

$$\xi_i = \epsilon_i\frac{(\Delta m_i^2 - m^2_{L_iH_1}/\epsilon_i) + \Delta B_i\mu t_\beta}{m^2_{\tilde\nu_i}}, \tag{8}$$

where $\Delta B_i = B - B_i$ and $\Delta m_i^2 = m^2_{H_1} - m^2_{L_i}$. It is most natural to assume that the tree mass (7) gives the heavier mass scale, $m_3 = \frac{M_Z^2}{F_N}\xi^2 c_\beta^2$. Considering the atmospheric neutrino mass-squared difference, $\Delta m^2_{\text{atm}} \approx 2.5\times10^{-3}\ \text{eV} \approx m_3^2$, we get

$$\xi c_\beta = 7.4\times10^{-7}\left(\frac{F_N}{M_Z}\right)^{1/2}\left(\frac{m_3}{0.05\ \text{eV}}\right)^{1/2}. \tag{9}$$

Since the two mixing angles, $\theta_{23} = \theta_{\text{atm}}$ and θ_{13}, satisfy

$$\tan\theta_{23} = \xi_2/\xi_3 \approx 1,$$
$$|\tan\theta_{13}| = |\xi_1|/\sqrt{\xi_2^2+\xi_3^2} \ll 1 \tag{10}$$

we need $\xi_1 < 0.3\xi_{2,3}$ to make small θ_{13} and $\xi_2 \approx \xi_3$ for near maximal atmospheric mixing. Thus, current neutrino oscillation data require

$$\xi_1 \ll \xi_2 \approx \xi_3 \approx 5.2\times10^{-7}\frac{1}{c_\beta}\left(\frac{F_N}{M_Z}\right)^{1/2}\left(\frac{m_3}{0.05\ \text{eV}}\right)^{1/2}. \tag{11}$$

Let us now consider how the one-loop mass arises in BRpV. In order to obtain the bi-large mixing of the atmospheric and solar neutrinos, one needs to introduce non-universality in soft terms at an ultraviolet scale [14]. In this Letter, we will assume flavour diagonal soft masses since off-diagonal terms are severely constrained by processes such as $\mu\to e\gamma$ and $\tau\to\mu\gamma$ [24]. Depending on the degree of the deviation from universality, we can consider two cases.

Case I. First, the non-universality of soft parameters can be assumed to be small. In this case, the quantities Δm_i^2, $m^2_{L_iH_1}/\epsilon_i$ and $\mu\Delta B_i$ are much smaller than the typical soft mass-squared $\tilde m^2$ so that the induced trilinear couplings of $\lambda'_{i33} = \epsilon_i h_b$ and $\lambda_{i33} = \epsilon_i h_\tau$ give the major contribution to the size of $m_2 \approx$

$\sqrt{\Delta m^2_{\rm sol}}$ [15,17] as in Eq. (5). Thus, this case is similar to TRpV discussed before.

However, we point out that there is a different way of reconciling the neutrino data with the baryogenesis requirement. Namely, we notice the possibility that the loop mass is larger than the tree mass. In this situation, the heavier neutrino mass scale can be produced mainly by the bottom–sbottom loop which can be rewritten from Eqs. (4) and (21) as follows

$$M^{\rm loop}_{ij} = \frac{3h_b^2}{8\pi^2}\epsilon_i\epsilon_j \frac{m_b^2(A_b+\mu\tan\beta)}{m^2_{\tilde b_1}-m^2_{\tilde b_2}} \ln\frac{m^2_{\tilde b_1}}{m^2_{\tilde b_2}}. \qquad (12)$$

As the above loop contribution determines the atmospheric neutrino mass and mixing, the condition (11) has to be replaced by

$$\epsilon_1 \ll \epsilon_2 \approx \epsilon_3 \approx 8\times 10^{-3} c_\beta \left(\frac{\tilde m}{300\ \mathrm{GeV}}\right)^{1/2}. \qquad (13)$$

As we will show, such large couplings $\epsilon_{2,3}$ cannot satisfy the baryogenesis constraint at all. But, ϵ_1 can be made arbitrarily small. Let us recall that it is sufficient to suppress lepton number violating couplings for just one lepton flavour. In our case, it is the electron number, which is implied by the smallness of θ_{13}. Now, in order for the tree mass (7) to produce the solar neutrino mass and mixing, we need

$$\xi_1 \sim \xi_2 \sim 3\times 10^{-7}\frac{1}{c_\beta}\left(\frac{F_N}{M_Z}\right)^{1/2}, \qquad (14)$$

where $\xi_1 \sim \xi_2$ is required by the large solar neutrino mixing and the overall size is to produce $m_2 = \sqrt{\Delta m^2_{\rm sol}}$.

Case II. Secondly, one can consider the scenario of large deviations of non-universality at the weak scale, implying that Δm_i^2, $m^2_{L_iH_1}/\epsilon_i$ and $\mu\Delta B_i$ are of the order $\tilde m^2$. In this case, the neutral scalar and neutralino exchange loops can give important contributions to the one-loop mass as long as $\tan\beta$ is not too large and the large misalignment between ξ_i and η_i is allowed [16]. The one-loop mass coming from the neutral scalar loops is roughly given by

$$M^{\rm loop}_{ij} \approx \frac{g^2}{64\pi^2} m_{\chi^0}\theta_{i\phi}\theta_{j\phi} B_0\big(m^2_{\chi^0}, m^2_\phi\big), \qquad (15)$$

where $B_0(x,y) = -\frac{x}{x-y}\ln\frac{x}{y} - \ln\frac{x}{Q^2} + 1$ and ϕ represents the neutral Higgs bosons, h, H and A. Neglecting the unimportant contribution of ξ_i, the variables $\theta_{i\phi}$ are approximately given by

$$\theta_{ih} \approx \eta_i s_\beta m_A^2 \frac{m^2_{\tilde\nu_i} c_{\alpha+\beta} - M_Z^2 c_{2\beta} c_{\alpha-\beta} - \varDelta_2 s_\alpha s_\beta}{(m^2_{\tilde\nu_i}-m_h^2)(m^2_{\tilde\nu_i}-m_H^2)},$$

$$\theta_{iH} \approx \eta_i s_\beta m_A^2 \frac{m^2_{\tilde\nu_i} s_{\alpha-\beta} - M_Z^2 c_{2\beta} s_{\alpha+\beta} + \varDelta_2 c_\alpha s_\beta}{(m^2_{\tilde\nu_i}-m_h^2)(m^2_{\tilde\nu_i}-m_H^2)},$$

$$\theta_{iA} \approx i\eta_i s_\beta \frac{m_A^2}{m_A^2 - m^2_{\tilde\nu_i}}, \qquad (16)$$

where $\eta_i \equiv \xi_i + \epsilon_i\Delta B_i/B$ and $m_{h,H}$ are the Higgs boson masses determined at one-loop level. Here, the one-loop correction of the Higgs potential is parametrized by the quantity $\varDelta_2$ which takes the form [24]

$$\varDelta_2 \equiv \frac{(m_A^2-m_h^2)(m_h^2 - M_Z^2 c^2_{2\beta}) + m_h^2 M_Z^2 s^2_{2\beta}}{m_A^2 s_\beta^2 - m_h^2 + M_Z^2 c_\beta^2}.$$

Then, the heavy Higgs mass m_H is determined by $m_H^2 = m_A^2 - m_h^2 + M_Z^2 + \varDelta_2$. The angle α diagonalizes the neutral Higgs boson masses and is obtained from the relation:

$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 + M_Z^2}{m_A^2 - M_Z^2 + \varDelta_2/c_{2\beta}}, \qquad -\frac{\pi}{2} \leqslant \alpha \leqslant 0.$$

Our convention for the pseudo-scalar Higgs boson mass is that $m_A^2 = -\mu B/c_\beta s_\beta$.

Requiring that $M^{\rm loop}_{ij}$ (15) determines the solar neutrino mass and mixing, one obtains

$$\theta_{1\phi} \sim \theta_{2\phi} \sim 6\times 10^{-6}\left(\frac{300\ \mathrm{GeV}}{m_{\chi^0}}\right)^{1/2}\left(\frac{m_\phi}{m_{\chi^0}}\right)\left(\frac{m_2}{8\ \mathrm{MeV}}\right). \qquad (17)$$

Again, the large mixing of solar neutrinos requires $\theta_{1\phi} \sim \theta_{2\phi}$. Remember that the above relation (17) is to be combined with the tree-level result (11) accounting for the atmospheric neutrino data.

3. Baryogenesis constraints on R-parity violation

In this section, we discuss how the R-parity violating couplings are constrained by the non-erasure condition of the baryon asymmetry before the electroweak phase transition. We begin with considering the interaction of Eq. (3) which gives the decay width for lepton number violating one-to-two body decays,

$$\Gamma_{12} = \frac{\pi\lambda^{(\prime)2}_{i33}}{192\zeta(3)}\frac{\tilde{m}^2}{T}. \tag{18}$$

The out-of-equilibrium condition, $\Gamma_{12} < H = 1.66 \times \sqrt{g_{\rm eff}}\,T^2/m_{\rm Pl}$, gives

$$\lambda'_{i33}, \lambda_{i33} < 2 \times 10^{-7}\left(\frac{\tilde{m}}{300\ \mathrm{GeV}}\right)^{1/2} \tag{19}$$

for $g_{\rm eff} = 915/4$. This is for $T \gg \tilde{m}$. An improved result which does not make this assumption was presented in [22] and shows that the $T/\tilde{m}$ dependence of Eq. (18) is very mild.

The constraints on the bilinear R-parity violating couplings are more involved. Extending the discussion of Ref. [23], we will identify the set of bilinear parameters which are constrained by our consideration. A key point to notice is that we are interested in the era when the electroweak symmetry breaking has not yet occurred. In this case, it is convenient to use the $SU(4)$ rotation in the 'superfields', L_i and H_1

$$L_i \to L_i + \epsilon_i H_1 \quad \text{and} \quad H_1 \to H_1 - \epsilon_i L_i \tag{20}$$

which eliminates of the ϵ_i term (valid up to $O(\epsilon_i)$) leaving invariant the gauge interactions. Its effect is to only generate the effective couplings

$$\lambda'_{i33} = \epsilon_i h_b \quad \text{and} \quad \lambda_{i33} = \epsilon_i h_\tau \tag{21}$$

for which the condition (19) is applied. Under the rotation (20), the scalar potential (6) becomes

$$\begin{aligned} V_{\rm soft} &= \mu(BH_1H_2 - \epsilon_i\Delta B_i L_i H_2) \\ &\quad + \left(m^2_{L_iH_1} - \epsilon_i\Delta m^2_i\right)L_iH_1^\dagger + \text{h.c.} \end{aligned} \tag{22}$$

which shows that the additional lepton number violating effect other than the induced trilinear couplings in Eq. (21) arises in the presence of the non-universal soft supersymmetry breaking parameters between the sleptons and Higgs bosons. In order to define the proper interaction vertices, one diagonalizes away such mixing mass terms, which can be done by the following approximate rotation among the scalar fields $\tilde{L}_i$, H_1 and $H'_2 \equiv i\tau_2 H_2^\dagger$:

$$\begin{aligned} \tilde{L}_i &\to \tilde{L}_i - \varepsilon_{i1}H_1 - \varepsilon_{i2}H'_2, \\ H_1 &\to H_1 + \varepsilon_{i1}\tilde{L}_i, \\ H'_2 &\to H'_2 + \varepsilon_{i2}\tilde{L}_i. \end{aligned} \tag{23}$$

Here the variables ε_{i1} and ε_{i2} are determined as

$$\begin{aligned} \varepsilon_{i1} &= \frac{(m^2_{H_2}+\mu^2-m^2_{L_i})(\epsilon_i\Delta m^2_i - m^2_{L_iH_1}) - \epsilon_i\mu^2 B\Delta B_i}{(m^2_{H_1}+\mu^2-m^2_{L_i})(m^2_{H_2}+\mu^2-m^2_{L_i}) - \mu^2B^2}, \\ \varepsilon_{i2} &= \frac{(m^2_{H_1}+\mu^2-m^2_{L_i})\epsilon_i\mu\Delta B_i - \mu B(\epsilon_i\Delta m^2_i - m^2_{L_iH_1})}{(m^2_{H_1}+\mu^2-m^2_{L_i})(m^2_{H_2}+\mu^2-m^2_{L_i}) - \mu^2B^2}. \end{aligned} \tag{24}$$

It is now useful to rewrite $\varepsilon_{i1,i2}$ in terms of the variables ξ_i and η_i dictating the neutrino mass matrix. Using the minimization condition of the Higgs and sneutrino fields, we obtain

$$\begin{aligned} \varepsilon_{i1} &\approx -\xi_i - \eta_i \frac{m^2_A s^2_\beta(m^2_{\tilde{\nu}_i} - M^2_Z c_{2\beta} + \frac{1}{2}\Delta_2)}{(m^2_{\tilde{\nu}_i} - m^2_A s^2_\beta)(m^2_{\tilde{\nu}_i} - M^2_Z c_{2\beta} + \frac{1}{2}\Delta_2) - m^2_{\tilde{\nu}_i} m^2_A c^2_\beta}, \\ \varepsilon_{i2} &\approx \frac{\eta_i}{t_\beta}\frac{m^2_A s^2_\beta m^2_{\tilde{\nu}_i}}{(m^2_{\tilde{\nu}_i} - m^2_A s^2_\beta)(m^2_{\tilde{\nu}_i} - M^2_Z c_{2\beta} + \frac{1}{2}\Delta_2) - m^2_{\tilde{\nu}_i} m^2_A c^2_\beta}. \end{aligned} \tag{25}$$

The variables $\varepsilon_{i1,i2}$ control the size of lepton number violating interactions whose couplings arise from the rotation (23) as follows:

$$\begin{aligned} \mathcal{L}_{\rm eff} &= h_\tau\varepsilon_{i1}\tilde{L}_iL_3E^c_3 + h_b\varepsilon_{i1}\tilde{L}_iQ_3D^c_3 + h_t\varepsilon_{i2}\tilde{L}'_iQ_3U^c_3 \\ &\quad + \frac{g'\varepsilon_{i1}}{\sqrt{2}}\left[H_1^\dagger L_i\tilde{B} + \tilde{L}_i^\dagger\tilde{H}_1\tilde{B}\right] + \frac{g'\varepsilon_{i2}}{\sqrt{2}}\tilde{L}_i^\dagger\tilde{H}'_2\tilde{B} \\ &\quad + \frac{g\varepsilon_{i1}}{\sqrt{2}}\left[H_1^\dagger\tau^aL_i\lambda^a + \tilde{L}_i^\dagger\tau^a\tilde{H}_1\lambda^a\right] \\ &\quad + \frac{g\varepsilon_{i2}}{\sqrt{2}}\tilde{L}_i^\dagger\tau^a\tilde{H}'_2\lambda^a + \text{h.c.}, \end{aligned} \tag{26}$$

where $\tilde{L}'_i \equiv i\tau_2\tilde{L}_i^\dagger$, τ^a are Pauli matrices and λ^a represent the $SU(2)$ gauginos.

Now, applying the constraint (19) to the couplings in Eqs. (21) and (26), we get the bounds on the bilinear couplings ϵ_i, ε_{i1} and ε_{i2} as follows

$$\begin{aligned} \epsilon_i &< 1.2 \times 10^{-5} c_\beta\left(\frac{\tilde{m}}{300\ \mathrm{GeV}}\right)^{1/2}, \\ \varepsilon_{i1} &< 3 \times 10^{-7}\left(\frac{m_{\chi^0}}{300\ \mathrm{GeV}}\right)^{1/2}, \\ \varepsilon_{i2} &< 2 \times 10^{-7} s_\beta\left(\frac{m_{L_i}}{300\ \mathrm{GeV}}\right)^{1/2}, \end{aligned} \tag{27}$$

where $\tilde{m}$ is the smallest mass of the sfermions involved in the λ'_{i33} term; L_i, Q_3 and D^c_3, m_χ is a gaugino mass involving in the process $\chi \to L_i H_1$ and the last equation comes from the process $\tilde{L}_i \to Q_3 U_3^c$.

Our baryogenesis constraints are summarized in Eqs. (19) and (27) for TRpV and BRpV, respectively. We can now discuss their compatibility with the neutrino mass matrix analyzed in the previous section.

TRpV: first of all, one sees a big contradiction between (5) and (19) in TRpV. As discussed below Eq. (5), the bi-large mixing of the atmospheric and solar neutrino oscillations require the couplings λ_{133}, λ_{233} as well as λ'_{233}, λ'_{333} to be of the same order. Thus, the baryogenesis constraint rules out the TRpV explanation (assuming universal soft terms) of the observed neutrino data.

BRpV: the situation can be different in BRpV where the neutrino masses are generated purely by bilinear R-parity violating couplings with non-universal soft masses, which can give much freedom.

Case I. Eqs. (13) and (27) shows that a strong hierarchy among ϵ_i is required: $\epsilon_1/\epsilon_{2,3} < 1.5 \times 10^{-3}$. This could be understood as a part of the flavour structure of the Yukawa couplings. A real difficulty in this option is that the degrees of non-universality, measured by ξ_i/ϵ_i as in Eq. (8), have to be arranged as follows

$$\frac{\xi_2}{\epsilon_2} \sim 4 \times 10^{-5} \frac{1}{c_\beta^2} \quad \text{and} \quad \frac{\xi_1}{\epsilon_1} > 2.6 \times 10^{-2} \frac{1}{c_\beta^2}. \tag{28}$$

This implies that the soft masses of the first and second generations have to follow a peculiar flavour structure: $m^2_{\tilde{\nu}_2} \simeq m^2_{H_1}$, $\Delta B_2 \mu t_\beta \ll m^2_{\tilde{\nu}_i}$, and $m^2_{H_1} \sim m^2_{\tilde{\nu}_1}$ or $\Delta B_1 \mu t_\beta \sim m^2_{\tilde{\nu}_1}$. The latter condition comes from our choice of $\xi_1/\epsilon_1 \lesssim 1$ which puts a limit of $\tan\beta \lesssim 6$. Once such an arrangement is accepted, it is not difficult to satisfy the requirements (14) and (27) simultaneously. For instance, taking the choice $\Delta B_1/B \ll 1$ (implying $\xi_1 \approx \eta_1$), one can see that the last two bounds in Eq. (27) can be well satisfied *if* $m_A > t_\beta m_{\tilde{\nu}_1}$.

Case II. In this case, one finds that the values of bilinear parameters reproducing the observed neutrino masses and mixing, (11) and (17), are an order of magnitude larger than the values permitted by the baryogenesis constraints (27). Therefore, accepting fine-tuning of 10%, it is possible to find some limited parameter space where both requirements are reconciled.

For a qualitative understanding of this, we first notice that the variables $\varepsilon_{i1,i2}$ and ξ_i or $\theta_{i\phi}$ have different dependencies on the input parameters. That is, comparing Eq. (25) with Eq. (16), we find that $\varepsilon_{i1,i2}$ (or ξ_i and η_i) can be made small while keeping $\theta_{i\phi} \sim 6 \times 10^{-6}$ (17) when the sneutrino mass $m_{\tilde{\nu}_i}$ is close to one of the Higgs boson masses, m_h, m_H and m_A. Barring cancellation, both terms in ε_{i1} (25) should be less than 3×10^{-7}, which can be achieved only for $i = 1$. That is, the electron number violating parameters, $\varepsilon_{11,12}$, can only be suppressed for our purpose. For such a degeneracy effect to become more effective, smaller $\tan\beta$ and smaller m_A are favoured. In the opposite case where $\tan\beta \gg 1$ and $m_A \gg m_h$, M_Z, one has $\tan 2\alpha \approx \tan 2\beta$ and thus

$$\begin{aligned}
&\theta_{1h} \sim c_\beta \eta_1 \frac{m_A^2 (m_h^2 + M_Z^2)}{(m^2_{\tilde{\nu}_1} - m_h^2)(m^2_{\tilde{\nu}_1} - m_H^2)}, \\
&\theta_{1H} \sim \eta_1 \frac{m_A^2}{(m^2_{\tilde{\nu}_1} - m_H^2)}, \\
&\varepsilon_{11} + \xi_1 \sim \eta_1 \frac{m_A^2}{(m^2_{\tilde{\nu}_1} - m_A^2)}, \qquad \varepsilon_{12} \sim (\varepsilon_{11} + \xi_1)/t_\beta.
\end{aligned} \tag{29}$$

From this, the desired situation of $\theta_{1h} \gg \theta_{1H} \sim \varepsilon_{11} + \xi_1$ can be obtained if a very fine-tuned relation $(m^2_{\tilde{\nu}_1} - m_h^2)/m_h^2 \ll 1/t_\beta$ is assumed. Obviously, such a tendency can be loosened for smaller values of $\tan\beta$ and m_A, which will be shown shortly by our numerical analysis.

Another way of suppressing ε_{i1} is to arrange a cancellation between two terms in ε_{i1}. From Eqs. (25) and (16), one typically has

$$\varepsilon_{i1} \sim -\xi_i - t_\beta \varepsilon_{i2} \quad \text{and} \quad \theta_{i\phi} \sim t_\beta \varepsilon_{i2} \tag{30}$$

for $m_{\tilde{\nu}_i} \gg M_Z$. Now, one can see that the conditions (27) and (17) can be satisfied for $t_\beta \sim 30$ with the cancellation in $\varepsilon_{i1} \sim \xi_i + \theta_{i\phi}$. Again, this can work only for the electron direction with $\xi_1 \sim \theta_{1\phi}$ since Eq. (11) shows $\xi_i \gg \theta_{i\phi} \sim 6 \times 10^{-6}$ for $i = 2, 3$ and large $\tan\beta$.

To quantify the above properties, we make a numerical calculation and find a set of points satisfying both the baryogenesis constraints and the atmospheric and solar neutrino data. For this, we use the exact formulae for the neutrino mass matrix derived in Ref. [16]. In Figs. 1–4, we plot the variable ε_{11} in terms of the

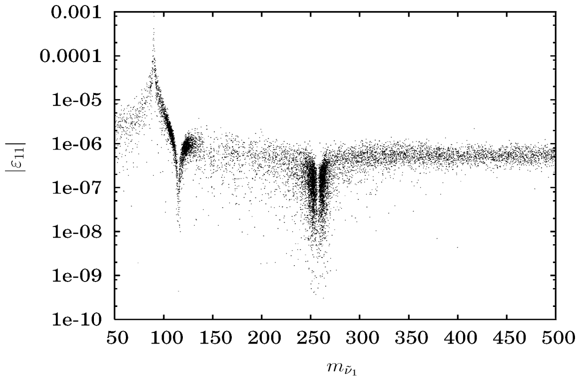

Fig. 1. The quantity ε_{11} is shown as a function of the electron sneutrino mass $m_{\tilde{\nu}_1}$ for all the points generating the required neutrino masses and mixing. The input values are $\tan\beta = 3$ and $m_A = 150$ GeV which correspond to $m_H = 257$ GeV.

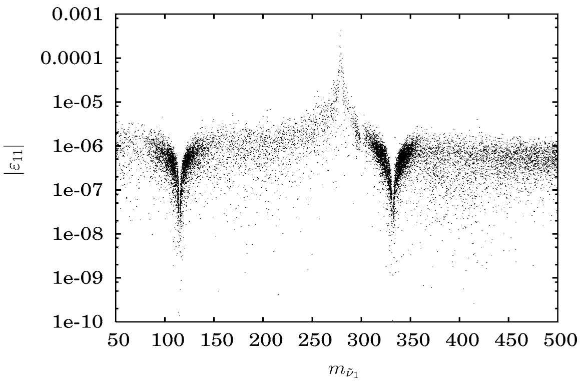

Fig. 2. Same as Fig. 1 with $m_A = 300$ GeV corresponding to $m_H = 332$ GeV.

electron sneutrino mass $m_{\tilde{\nu}_1}$ for all the points accommodating all the observed neutrino data. We fix the light Higgs boson mass $m_h = 115$ GeV and vary of $\tan\beta = 3, 10$ and $m_A = 150, 300$ GeV for each figure. As alluded before, the baryogenesis constraint, i.e., $\varepsilon_{11} < 10^{-7}$, is shown to be satisfied by some parameter space with lower $\tan\beta$ and smaller m_A (Fig. 1) where $m_{\tilde{\nu}_1}$ is closed to m_h and m_H. For larger $\tan\beta$ and m_A, one also finds some scattered points for large $m_{\tilde{\nu}_1}$ where the cancellation can take place. Our analysis shows that the allowed parameter space is very restricted but one cannot exclude the bilinear model from our cosmological consideration.

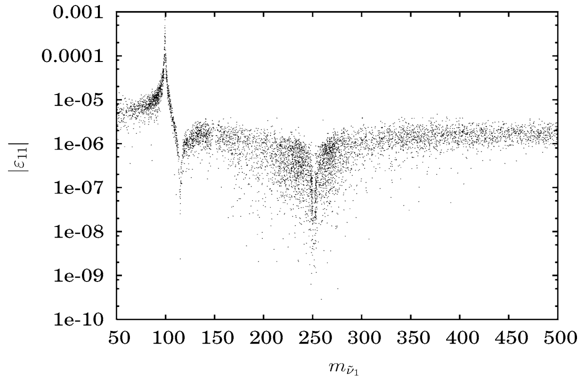

Fig. 3. Same as Fig. 1 with $\tan\beta = 10$ and $m_A = 150$ GeV corresponding to $m_H = 251$ GeV.

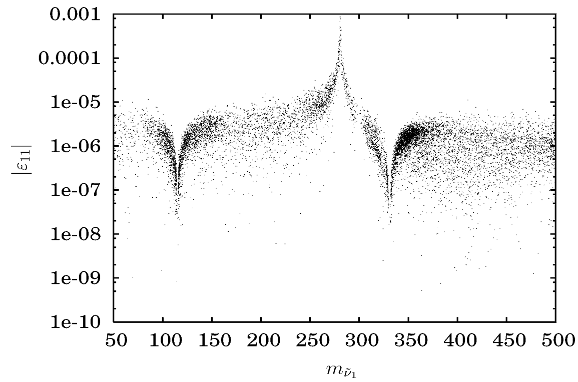

Fig. 4. Same as Fig. 3 with $m_A = 300$ GeV corresponding to $m_H = 331$ GeV.

4. Conclusions

We have investigated how a primordially generated B–L asymmetry can be preserved in the R-parity violating version of supersymmetric standard model, while simultaneously providing the currently favoured form of the neutrino mass matrix. Such a baryogenesis constraint cannot be satisfied if the trilinear R-parity violating couplings are introduced to explain the atmospheric and solar neutrino masses and mixing under the assumption of the universal soft supersymmetry breaking masses. In the bilinear model, the observed neutrino data can be accommodated if non-universality is allowed. Our analysis shows that the non-erasure condition, although strongly restricting the parameter space of good solutions, can be satisfied by suppressing the electron number violating parameters, which is related to the smallness of the angle θ_{13}. In the case of a large violation of the universality, the near degeneracy of the electron sneutrino with a light or heavy Higgs boson, or some cancellation between two contributions to ε_{11} is required. For a small violation of the universality, we argued that the situation of the loop mass dominating over the tree mass is preferred contrary to the usual consideration.

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