Neutrino Masses and Mixings in SUSY with Broken R-Parity

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Abstract

The simplest unified extension of the Minimal Supersymmetric Standard Model with bilinear R–Parity violation provides a predictive scheme for neutrino masses which can account for the observed atmospheric and solar neutrino anomalies. Despite the smallness of neutrino masses R-parity violation is observable at present and future high-energy colliders, providing an unambiguous cross-check of the model.

1 Introduction

The announcement of high statistics atmospheric neutrino data by the SuperKamiokande collaboration [1] has confirmed the deficit of muon neutrinos, especially at small zenith angles, opening a new era in neutrino physics. Although there may be alternative solutions of the atmospheric neutrino anomaly [2] it is fair to say that the simplest interpretation of the data is in terms of $\nu_\mu$ to $\nu_\tau$ flavor oscillations with maximal mixing. This excludes a large mixing among $\nu_\tau$ and $\nu_e$ [3], in agreement also with the CHOOZ reactor data [3]. On the other hand the persistent disagreement between solar neutrino data and theoretical expectations [4] has been a long-standing problem in physics. Recent solar neutrino data [5] are consistent with both vacuum oscillations and MSW conversions. In the latter case one can have either the small or the large mixing angle solutions, with the latter being clearly preferred [3].

Many attempts have appeared in the literature to explain the data. Here we review recent results [6] obtained in a model [7] which is a simple extension of the MSSM with bilinear R-parity violation (BRpV). This model, despite being a minimal extension of the MSSM, can explain the solar and atmospheric neutrino data. Its most attractive feature is that it gives definite predictions for accelerator physics for the same range of parameters that explain the neutrino data.

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2 Bilinear R-Parity Violation (BRpV)

2.1 The Model

The superpotential $W$ is given by

$$W = \varepsilon_{ab} \left[ h_{U}^{ ij} \bar{Q}^{i}_{a} \bar{U}^{b}_{4} + \tilde{h}_{U}^{ ij} \bar{Q}^{i}_{a} \tilde{D}^{b}_{i} \tilde{H}^{a}_{u} + h_{E}^{ ij} \tilde{L}^{b}_{i} \tilde{R}^{j}_{j} - \mu \tilde{H}^{a}_{u} \tilde{H}^{b}_{u} + \epsilon_{i} \tilde{L}^{a}_{i} \tilde{H}^{b}_{u} \right]$$

(1)

while the set of soft supersymmetry breaking terms are

$$V_{soft} = M_{Q}^{ij} \bar{Q}^{i}_{a} \bar{Q}^{j}_{a} + M_{U}^{ij} \bar{U}^{i}_{a} \bar{U}^{j}_{a} + M_{D}^{ij} \bar{D}^{i}_{a} \bar{D}^{j}_{a} + M_{L}^{ij} \bar{L}^{i}_{a} \bar{L}^{j}_{a} + M_{R}^{ij} \bar{L}^{i}_{a} \bar{R}^{j}_{j}$$

$$+ m_{H_{d}}^{2} H_{d}^{a} H_{d}^{a} + m_{H_{u}}^{2} H_{u}^{a} H_{u}^{a} - \sum_{i} \frac{1}{2} M_{i} \lambda_{i} \lambda_{i} + \varepsilon_{ab} \left( A_{U}^{ij} \bar{Q}^{i}_{a} \bar{D}^{j}_{a} b_{4} H_{d}^{b} \right)$$

$$+ A_{D}^{ij} \bar{Q}^{i}_{a} \tilde{D}^{j}_{a} H_{d}^{a} + A_{E}^{ij} \bar{L}^{i}_{a} \tilde{R}^{j}_{j} H_{d}^{a} - B_{1} H_{d}^{a} H_{d}^{b} + B_{2} \varepsilon_{i} \tilde{L}^{a}_{i} H_{u}^{b} \right] + h.c$$

(2)

The bilinear R-parity violating term cannot be eliminated by superfield redefinition. The reason is [8] that the bottom Yukawa coupling, usually neglected, plays a crucial role in splitting the soft-breaking parameters $B$ and $B_{i}$ as well as the scalar masses $m_{H_{d}}^{2}$ and $M_{L}^{2}$, assumed to be equal at the unification scale. The BRpV model is a 1(3) parameter(s) generalization of the MSSM. It can be thought as an effective model showing the more important features of the Spontaneous Broken R-parity model (SBRP) [9, 10] at the weak scale. The mass matrices, charged and neutral currents, are similar to the SBRP-model if we identify

$$\epsilon \equiv v_{R} h_{\nu}$$

(3)

The model has the MSSM as a limit when $\epsilon_{i} \rightarrow 0$.

2.2 Radiative Breaking

At $Q = M_{GUT}$ we assume the standard minimal supergravity unifications assumptions,

$$A_{1} = A_{a} = A_{\tau} \equiv A, B = B_{2} = A - 1, \quad m_{H_{d}}^{2} = m_{H_{u}}^{2} = M_{L}^{2} = M_{R}^{2} = M_{Q}^{2} = M_{U}^{2} = M_{D}^{2} = m_{0}^{2} \quad M_{3} = M_{2} = M_{1} = M_{1/2}$$

(4)

In order to determine the values of the Yukawa couplings and of the soft breaking scalar masses at low energies we first run the RGE’s from the unification scale $M_{GUT} \sim 10^{16}$ GeV down to the weak scale. For details see [3, 4].

3 Tree Level Neutrino Masses and Mixings

3.1 Neutral fermion mass matrix

In the basis $\psi^{0T} = (-i \lambda', -i \lambda^{3}, \tilde{H}_{d}^{1}, \tilde{H}_{u}^{2}, \nu_{e}, \nu_{\mu}, \nu_{\tau})$ the neutral fermions mass terms in the Lagrangian are given by

$$\mathcal{L}_{m} = -\frac{1}{2} (\psi^{0})^{T} M_{N} \psi^{0} + h.c.$$  

(5)
where the neutralino/neutrino mass matrix is

$$M_{N} = \begin{bmatrix} M_{\chi} & m^T \\ m & 0 \end{bmatrix}$$ (6)

with

$$M_{\chi} = \begin{bmatrix} M_{1} & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_{2} & \frac{1}{2}gv_d & \frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{bmatrix} ; \quad m = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$ (7)

where $$a_i = (-\frac{1}{2}g'v_i, \frac{1}{2}gv_i, 0, \epsilon_i)$$. This neutralino/neutrino mass matrix is diagonalized by

$$N^* M_{N} N^{-1} = \text{diag}(m_{\chi_1}^{\text{eff}}, m_{\chi_2}^{\text{eff}}, m_{\chi_3}^{\text{eff}}, m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$ (8)

### 3.2 Approximate diagonalization of mass matrices

If the $R_p$ parameters are small, then

$$\xi = m \cdot M_{\chi}^{-1} \Rightarrow \forall \xi_{ij} \ll 1$$ (9)

one can find an approximate solution for the mixing matrix $N$. Explicit expressions can be found in Ref. [6]. In leading order in $\xi$ the mixing matrix $N$ is given by,

$$N^* = \begin{pmatrix} N^* & 0 \\ 0 & V^T_{\nu} \end{pmatrix} \begin{pmatrix} 1 - \frac{1}{2}\xi^\dagger \xi & \xi^\dagger \\ \xi & 1 - \frac{1}{2}\xi \xi^\dagger \end{pmatrix}$$ (10)

This decomposition block–diagonalizes $M_N$ approximately to the form diag($m_{\text{eff}}, M_{\chi}$), where

$$m_{\text{eff}} = -m \cdot M_{\chi}^{-1} m^T = \frac{M_1g^2 + M_2g'^2}{4 \det(M_{\chi})} \begin{pmatrix} \Lambda_e^2 & \Lambda_e\Lambda_{\mu} & \Lambda_e\Lambda_{\tau} \\ \Lambda_e\Lambda_{\mu} & \Lambda_{\mu}^2 & \Lambda_{\mu}\Lambda_{\tau} \\ \Lambda_e\Lambda_{\tau} & \Lambda_{\mu}\Lambda_{\tau} & \Lambda_{\tau}^2 \end{pmatrix}.$$ (11)

The submatrices $N$ and $V_{\nu}$ in Eq. (10) diagonalize $M_{\chi}$ and $m_{\text{eff}}$

$$N^* M_{\chi} N^\dagger = \text{diag}(m_{\chi_1}^{\text{eff}}, m_{\chi_2}^{\text{eff}}, m_{\chi_3}^{\text{eff}}, m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) ; \quad V_{\nu}^T m_{\text{eff}} V_{\nu} = \text{diag}(0, 0, m_{\nu}),$$ (12)

where

$$m_{\nu} = Tr(m_{\text{eff}}) = \frac{M_1g^2 + M_2g'^2}{4 \det(M_{\chi})} |\tilde{\Lambda}|^2.$$ (13)

### 4 One Loop Neutrino Masses and Mixings

#### 4.1 Definition

The Self–Energy for the neutralino/neutrino is
\[ i \xrightarrow{\text{circle}} j \quad \equiv i \left\{ /p \left[ P_L \Sigma^L_{ij} + P_R \Sigma^R_{ij} \right] - \left[ P_L \Pi^L_{ij} + P_R \Pi^R_{ij} \right] \right\} \] (14)

Then

\[ M_{ij}^{\text{pole}} = M_{ij}^{\text{DR}}(\mu_R) + \Delta M_{ij} \] (15)

with

\[ \Delta M_{ij} = \left[ \frac{1}{2} \left( \Pi^V_{ij}(m_i^2) + \Pi^V_{ij}(m_j^2) \right) - \frac{1}{2} \left( m_{\chi_i} \Sigma^V_{ij}(m_i^2) + m_{\chi_j} \Sigma^V_{ij}(m_j^2) \right) \right]_{\Delta=0} \] (16)

where

\[ \Sigma^V = \frac{1}{2} \left( \Sigma^L + \Sigma^R \right) \quad ; \quad \Pi^V = \frac{1}{2} \left( \Pi^L + \Pi^R \right) \] (17)

and

\[ \Delta = \frac{2}{4-d} - \gamma_E + \ln 4\pi \] (18)

4.2 Diagrams Contributing

In a generic way the diagrams contributing are

These diagrams can be calculated in a straightforward way. For instance the \( W \) diagram in the \( \xi = 1 \) gauge gives

\[ \Sigma^V_{ij} = -\frac{1}{16\pi^2} \sum_{k=1}^5 2 \left( O^{\text{ncw}}_{Ljk} O^{\text{cnw}}_{Lki} + O^{\text{ncw}}_{Rjk} O^{\text{cnw}}_{Rki} \right) B_1(p^2, m_k^2, m_W^2) \]

\[ \Pi^V_{ij} = -\frac{1}{16\pi^2} \sum_{k=1}^5 (-4) \left( O^{\text{ncw}}_{Ljk} O^{\text{cnw}}_{Rki} + O^{\text{ncw}}_{Rjk} O^{\text{cnw}}_{Lki} \right) m_k B_0(p^2, m_k^2, m_W^2) \]

where \( B_0 \) and \( B_1 \) are the Passarino-Veltman functions, and \( O^{\text{cnw}}, O^{\text{ncw}} \) are coupling matrices. Explicit expressions can be found in [6].

4.3 Gauge Invariance

When calculating the self–energies the question of gauge invariance arises. We have performed a careful calculation in an arbitrary \( R_\xi \) gauge and showed [6] that the result was independent of the gauge parameter \( \xi \).
4.4 The One–Loop Mass Matrix

The one–loop corrected mass matrix is

\[ M_{1L} = M_{\text{diag}}^0 + \Delta M_{1L} \]  \hfill (19)

where

\[ M_{\text{diag}}^0 = \mathcal{N} M_N \mathcal{N}^T \]  \hfill (20)

Now we diagonalize the 1–loop mass matrix

\[ M_{\text{diag}}^{1L} = \mathcal{N}' M_{1L} \mathcal{N}'^T \]  \hfill (21)

Then the mass eigenstates are related to the weak basis states by

\[ \chi_{0}^{\text{mass}} = \mathcal{N}_{1L} \chi_{0}^{\text{weak}} \]  \hfill (22)

with

\[ \mathcal{N}^{1L} = \mathcal{N}' \mathcal{N} \]  \hfill (23)

The usual convention in neutrino physics

\[ \nu_\alpha = U_{\alpha k} \nu_k \]  \hfill (24)

is recovered in our notation as

\[ U_{\alpha k} = \mathcal{N}_{4+k,4+\alpha}^{1L} \]  \hfill (25)

4.5 Approximate Formulas for Masses and Mixings

4.5.1 The masses

Looking at the numerical results we found that the most important contribution came from the bottom-sbottom loop. To gain an analytical understanding of the results we expanded the exact results in the small parameters. The result is

\[ M_\nu \simeq c_0 \begin{pmatrix} \Lambda_1 \Lambda_1 & \Lambda_1 \Lambda_2 & \Lambda_1 \Lambda_3 \\ \Lambda_2 \Lambda_1 & \Lambda_2 \Lambda_2 & \Lambda_2 \Lambda_3 \\ \Lambda_3 \Lambda_1 & \Lambda_3 \Lambda_2 & \Lambda_3 \Lambda_3 \end{pmatrix} \begin{pmatrix} \epsilon_1 \epsilon_1 & \epsilon_1 \epsilon_2 & \epsilon_1 \epsilon_3 \\ \epsilon_2 \epsilon_1 & \epsilon_2 \epsilon_2 & \epsilon_2 \epsilon_3 \\ \epsilon_3 \epsilon_1 & \epsilon_3 \epsilon_2 & \epsilon_3 \epsilon_3 \end{pmatrix} + c_1 \begin{pmatrix} \epsilon_1 \epsilon_1 & \epsilon_1 \epsilon_2 & \epsilon_1 \epsilon_3 \\ \epsilon_2 \epsilon_1 & \epsilon_2 \epsilon_2 & \epsilon_2 \epsilon_3 \\ \epsilon_3 \epsilon_1 & \epsilon_3 \epsilon_2 & \epsilon_3 \epsilon_3 \end{pmatrix} \]  \hfill (26)

where

\[ c_0 = \frac{M_1 g^2 + M_2 g'^2}{4 \det(M_\phi^0)} \quad ; \quad c_1 = \frac{3}{16 \pi^2} m_b \sin 2\theta_b \frac{h_b^2}{\mu^2} \log \frac{m_{b_2}^2}{m_{b_1}^2} \]  \hfill (27)

Diagonalization of the mass matrix gives

\[ m_{\nu_1} = 0 \]  \hfill (28)

\[ m_{\nu_2} \simeq \frac{3}{16 \pi^2} m_b \sin 2\theta_b \frac{h_b^2}{\mu^2} \log \frac{m_{b_2}^2}{m_{b_1}^2} \frac{(\bar{\epsilon} \times \bar{\Lambda})^2}{|\bar{\Lambda}|^2} \]  \hfill (29)

\[ m_{\nu_3} \simeq \frac{M_1 g^2 + M_2 g'^2}{4 \det(M_\phi^0)} |\bar{\Lambda}|^2 \]  \hfill (30)
The formula for $m_{\nu_3}$ is the tree-level formula that we used to fix the scale of the atmospheric neutrinos by choosing $|\vec{\Lambda}|$. The quality of the approximation formula for $m_{\nu_2}$ can be seen in Fig. 1. Only for small $\tan \beta$ and very small $b, \bar{b}$ mixing the approximation can lead, in some cases, to incorrect results. Details of the derivation can be found in Ref. [11] where the second most important contribution, coming from the loop with charged Higgs/charged leptons, is also discussed.

4.5.2 The mixings

The atmospheric angle is easily obtained in terms of the ratio $\Lambda_2/\Lambda_3$. For the solar angle in the same approximation we also get a simple formula [11],

$$\tan^2 \theta_{\text{sol}} = \frac{2\epsilon^2}{(\epsilon_2 + \epsilon_3)^2} \tag{31}$$

that is also in very good agreement with the exact result.

5 Results for the Solar and Atmospheric Neutrinos

5.1 The masses

The BRpV model produces a hierarchical mass spectrum for almost all choices of parameters. The largest mass can be estimated by the tree level value using Eq. (30). Correct $\Delta m^2_{\text{atm}}$ can be easily obtained by an appropriate choice of $|\vec{\Lambda}|$. The mass scale for the solar neutrinos is generated at 1–loop level and therefore depends in a complicated way in the model parameters. However, in most cases the result of Eq. (29) is a good approximation and there is no problem in having both $\Delta m^2_{\text{atm}}$ and $\Delta m^2_{\text{solar}}$ set to the correct scales.

5.2 The mixings

Now we turn to the discussion of the mixing angles. We have found that if $\epsilon^2/|\vec{\Lambda}| \ll 100$ then the 1–loop corrections are not larger than the tree level results and the flavor
composition of the 3rd mass eigenstate is approximately given by
\[ U_{\alpha 3} \approx \Lambda_{\alpha} / |\tilde{\Lambda}| \]  
(32)

As the atmospheric and reactor neutrino data tell us that \( \nu_\mu \to \nu_\tau \) oscillations are preferred over \( \nu_\mu \to \nu_e \), we conclude that
\[ \Lambda_e \ll \Lambda_\mu \simeq \Lambda_\tau \]  
(33)

are required for BRpV to fit the data. This is sown in Fig. 2 a). We cannot get so easily maximal mixing for solar neutrinos, because in this case \( U_{e3} \) would be too large contradicting the CHOOZ result as shown in Fig. 2 b).

We have then two scenarios. In the first one, that we call the \textit{mSUGRA} case, we have universal boundary conditions of the soft SUSY breaking terms. In this case we can show \[ 6 \] that
\[ \epsilon_e / \epsilon_\mu \simeq \Lambda_e / \Lambda_\mu \]  
(34)

Then from Fig. 2 b) and the CHOOZ constraint on \( U_{e3}^2 \), we conclude that \textit{both} ratios in Eq. (34) have to be small. Then from Fig. 3 we conclude that the only possibility is the small angle mixing solution for the solar neutrino problem. In the second scenario, which we call the \textit{MSSM} case, we consider non–universal boundary conditions of the soft SUSY breaking terms. We have shown that even a very small deviation from universality of the soft parameters at the GUT scale relaxes this constraint. In this case
\[ \epsilon_e / \epsilon_\mu \neq \Lambda_e / \Lambda_\mu \]  
(35)

Then we can have at the same time \textbf{small} \( U_{e3}^2 \) determined by \( \Lambda_e / \Lambda_\mu \) as in Fig. 2 b) and \textbf{large} \( \tan^2(\theta_{\text{solar}}) \) determined by \( \epsilon_e / \epsilon_\mu \) as in Fig. 3 b).
6 Probing Neutrino Mixing via Neutralino Decays

If R-parity is broken, the neutralino is unstable and it will decay through the following channels: $\tilde{\chi}_0^0 \rightarrow \nu_i \nu_j \nu_k, \nu_i \ell^+_l \ell^-_k, l^+_l q \bar{q}', \nu_i \gamma$. It was shown in Ref. [12], that the neutralino decays well inside the detectors and that the visible decay channels are quite large. This was fully discussed in Ref. [12] and is illustrated in Fig. 4. We have seen before that the ratios $|\Lambda_i/\Lambda_j|$ and $|\epsilon_i/\epsilon_j|$ were very important in the choice of solutions for the neutrino mixing angles. What is exciting now, is that these ratios can be measured in accelerator experiments. In Fig. 5 a) we show the ratio of branching ratios for semileptonic LSP decays into muons and taus: $BR(\chi \rightarrow \mu q\bar{q}')/BR(\chi \rightarrow \tau q\bar{q}')$ as function of $\tan^2 \theta_{atm}$. We can see that there is a strong correlation. In Fig. 5 b) is shown the ratio of branching ratios for semileptonic LSP decays into muons and taus: $BR(\chi \rightarrow e q\bar{q}')/BR(\chi \rightarrow \mu q\bar{q}')$ as function of $U^2_{e3}$. Again we obtain a strong correlation. The spread on those figures can in fact be explained by the fact that we do not know the SUSY parameters. This is illustrated in Fig. 6 where we considered that SUSY was already discovered with the following values for the parameters,

$$M_2 = 120 \text{ GeV}, \mu = 500 \text{ GeV}, \tan \beta = 5, m_0 = 500 \text{ GeV}, A = -500 \text{ GeV} \quad (36)$$

7 Conclusions

The Bilinear R-Parity Violation Model is a simple extension of the MSSM that leads to a very rich phenomenology. We have shown that the radiative breaking of the Gauge Symmetry can be achieved in this BRpV Model. We have calculated the one–loop corrected masses and mixings for the neutrinos in a completely consistent way, including the RG equations and correctly minimizing the potential. We have shown that it is possible to get easily maximal mixing for the atmospheric neutrinos and both small and large angle MSW. We emphasize that the lightest neutralino decays inside the detectors, thus leading to a very different phenomenology than the MSSM. If the model is to explain solar
Figure 4: a) Decay length of $\tilde{\chi}_1^0$ as function of $m_{\tilde{\chi}_1^0}$. b) Invisible branching ratio of the $\tilde{\chi}_1^0$ as function of $m_{\tilde{\chi}_1^0}$

Figure 5: Ratios of semileptonic branching ratios as functions of $\tan^2 \theta_{atm}$ and $U_{e3}^2$.

and atmospheric neutrino problems many signals will arise at future colliders. These will probe the neutrino mixing parameters. Thus the model is easily falsifiable!

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Figure 6: The same as in Fig. 5 but for a unique SUSY point.

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