Stop Decays with R–Parity Violation and the Neutrino Mass

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The atmospheric and solar neutrino problems can be explained in a supersymmetric scenario where R–parity is broken bilinearly. Within this context we explore the decays of the top squark. We find that the Rp violating decay $\tilde{t}_1 \rightarrow b\tau$ can easily dominate over the Rp conserving decay $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ and sometimes also over the decay $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$. We study the implications of non–universal boundary conditions at the GUT scale.

The SuperKamiokande collaboration has confirmed the deficit of muon neutrinos from atmospheric neutrino data [1]. The simplest interpretation of the data is through $\nu_\mu \rightarrow \nu_\tau$ flavour oscillations with maximal mixing. This experimental observation has profound implications on one of the fundamental problems in modern physics, namely, the pattern of fermion masses and mixings, and the origin of mass. Recently, a supersymmetric solution to this problem was proposed [2], based on an extension of the Minimal Supersymmetric Standard Model (MSSM) where R–Parity and lepton number are violated through bilinear terms in the superpotential (BRpV) [3,4].

The model can be embedded into supergravity (SUGRA) with universal boundary conditions at the Grand Unification scale (GUT), and radiative electroweak breaking [5], in which case, this is a one parameter extension of Minimal SUGRA.

The superpotential contains the following bilinear terms

$$W = -\mu \hat{H}_d \hat{H}_u + \epsilon_i \hat{L}_i \hat{H}_u + \ldots (1)$$

where $\epsilon_i$ are BRpV parameters with units of mass. The rest of the superpotential corresponds to the usual Rp conserving Yukawa terms. A tree level neutrino mass is generated through neutrino mixing with neutralinos and a see-saw type mechanism. If the $\epsilon_i$ are small, the tree level neutrino mass can be approximated to

$$m_\nu \approx \frac{g^2 M_1 + g'^2 M_2}{4 \text{det}(M_\chi)} |\Lambda|^2$$

where $\Lambda_i = \mu v_i + v_d \epsilon_i$, and $v_i$ are the sneutrino vevs [6]. The parameters $\Lambda_i$ are proportional to the vevs of the sneutrinos in the basis where $\epsilon$ terms are removed from the superpotential. The $\Lambda_i$ play a crucial role in the determination of the atmospheric angle. For example, in Fig. 1 we have

![Figure 1. Atmospheric angle as a function of $|\Lambda_\mu/\Lambda_\tau|$ for $|\Lambda_e| = 0.1|\Lambda_\tau|$.](image-url)

the atmospheric angle as a function of $|\Lambda_\mu/\Lambda_\tau|$ for $|\Lambda_e| = 0.1|\Lambda_\tau|$. Maximality is obtained for $|\Lambda_\mu| \approx |\Lambda_\tau|$ as long as $|\Lambda_e|$ is small. The solar neutrino problem can also be solved by this mechanism [6].
In the determination of neutrino masses and mixing angles the one–loop contributions are essential [7,2]. The main loops are given by

\[ \nu \nu \nu \nu + \tilde{\chi}^+ + \tilde{\text{b}}^+, H^-, \tilde{\text{b}}, H^- \tilde{\chi}^+ + W^- \]

where the bottom–sbottom contribution is the most important one. One–loop contributions increase as \( \tan \beta \) increases and as \( m_0 \) decreases [2]. Changinos mix with charged sleptons, therefore the last ones also contribute, although less importantly. The phenomenological implications of this mixing in the tau sector can be found in [8].

In particular, the mixing does not spoil the well measured \( Z\tau\tau \) and \( W\tau\bar{\nu}_\tau \) couplings.

In BRpV neutral Higgs bosons mix with sneutrinos. This mixing does not affect the upper bound on the neutral CP-even Higgs mass, although in general lowers \( m_h \) in a few GeV [5]. Interestingly, the SUSY solution to the atmospheric and solar neutrino problems requires low \( \tan \beta \) which in turn implies low Higgs mass \( m_h \) [9]. In fact, it was found that \( \tan \beta \lesssim 10 \) and \( m_h \lesssim 115 \text{ GeV} \) is required to solve the neutrino problems. Small values of \( \tan \beta \) are already been explored by neutral Higgs searches, preliminary ruling out \( 1 < \tan \beta \lesssim 1.8 \) [10].

Beside the effects on the neutrino sector, BRpV has important implications on the phenomenology of supersymmetric particles. To study them, it is usually a good approximation to consider BRpV only in the tau sector: \( \epsilon_1 = \epsilon_2 = 0, \epsilon_3 \neq 0 \). In this case, the tau–neutrino mass is the only non–zero, is given by

\[ m_{\nu_\tau} \approx \frac{g^2}{2M} \nu_3^2 \]

and depends only on the tau–neutrino vev \( \nu_3^2 \) in the rotated basis. In this way, \( m_{\nu_\tau} \) gives a good order of magnitude of the neutrino masses in the complete theory when the details in the neutrino sector are not relevant. We have made a scan over all the parameters of the theory and in Fig. 2 we plot the tau–neutrino mass as a function of the parameter \( \xi \equiv \Lambda^2 \). We appreciate that \( m_{\nu_\tau} \) values can be obtained from the collider upper bound of 18 MeV [11] down to eV or smaller.

The phenomenology of the top–squarks (stops) is also affected by BRpV [13,14]. The Rp violating couplings of the stop are governed by \( \epsilon_3 \) and not by the neutrino mass, which makes them potentially large. In the following we study in detail the Rp violating decay mode \( \tilde{t}_1 \to b\tau \) and compare it with the Rp conserving decays \( \tilde{t}_1 \to c\chi_3^0 \) and \( \tilde{t}_1 \to b\chi_1^+ \). In Fig. 3 we plot the regions of parameter space relevant to the three decay modes mentioned. We work with BRpV embedded into SUGRA with universal scalar \( m_0 \) and gaugino \( M_1/2 \) masses at the GUT scale.

We do not study here the decay mode \( t \to bH^+ \). The charged Higgs mixes with the staus and their rich phenomenology in BRpV can be found in [12]. In particular, a charged Higgs lighter than in the MSSM, even after radiative corrections [15], can be found in global BRpV. In BRpV–SUGRA though, the charged Higgs is usually heavier. In addition, the constraints on the charged Higgs mass from the CLEO measurement for \( B(b \to s\gamma) \) [16] in the MSSM [17] are relaxed in BRpV [18].

The first issue we point out is that the one step approximation of the RGE’s in the analytic determination of \( \Gamma(\tilde{t}_1 \to c\chi_3^0) \) [19] is usually off by one order of magnitude or more. In Fig. 4 we compare the exact solution [13] with the one–step approximation for four different values of \( \tan \beta \) and
Figure 3. Kinematical regions in the stop-chargino mass plane relevant for the decay modes $\tilde{t}_1 \rightarrow b\tau$, $\tilde{t}_1 \rightarrow c\tilde{\chi}^+_i$, and $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$.

$M_{1/2}$. Note that the approximation can fail for several orders of magnitude for one of the examples. The main reason for this behaviour is that the evolution of $A_b$ depends strongly on $M_{1/2}$ and $\tan \beta$, and this dependence is lost in the one-step approximation.

In Fig. 5 we compare the branching ratios of the Rp violating decay mode $\tilde{t}_1 \rightarrow b\tau$ and the Rp conserving decay $\tilde{t}_1 \rightarrow c\tilde{\chi}^+_1$ in the regions of parameter space where the decay $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$ is closed. We observe that even for small values of the BRpV parameters $\epsilon_3$ and $v_3$ it is very easy for the Rp violating decay mode to dominate: $\mathcal{B}(\tilde{t}_1 \rightarrow b\tau) > 0.9$. This has crucial consequences in the experimental strategies in the search for top squarks in the region where the stop is roughly lighter than the chargino. We note that $\tilde{t}_1 \rightarrow b\tau$ can dominate even for neutrino masses of the order of $10^{-2} < m_{\nu_{\tau}} < 10^{-1}$ eV [13].

If $m_{\tilde{t}_1} > m_{\tilde{\chi}^+_i} + m_b$ then the stop can decay also into a chargino and a bottom quark. In Fig. 3 we compare this decay mode with the Rp violating one. We show in the plane $m_{\tilde{t}_1} - m_{\tilde{\chi}^+}$ the regions where the RpV decay $\mathcal{B}(\tilde{t}_1 \rightarrow b\tau)$ dominates over the Rp conserving decay $\mathcal{B}(\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1)$. In the shaded region the decay $\tilde{t}_1 \rightarrow b\tilde{\chi}^+_1$ is not allowed. Between the shaded region and the inclined lines we have an RpV decay rate larger than the Rp conserving one. For small values of the parameter $\epsilon_3$ the RpV decay dominates only if close to the threshold, where a large kinematical suppression is present.

It is interesting to correlate these branching ratios with the neutrino mass, which in first approximation it is given by eq. (3). The sneutrino vev is determined by the minimization of the scalar potential, which in BRpV involve three tadpole equations. In models with universality of scalar masses at the GUT scale the sneutrino vev at tree level is [20]

$$v'_3 = -\frac{\epsilon_3 \mu'}{\mu' v_2^2} (v'_1 \Delta m^2 + \mu' v_2 \Delta B)$$

(4)

where $\Delta m^2 = m_{\tilde{H}_1}^2 - m_{\tilde{H}_3}^2$ and $\Delta B = B_3 - B$ are evaluated at the weak scale. With soft universality at the GUT scale, these two differences are naturally small because they are radiatively generated and proportional to the bottom Yukawa coupling squared. In order to have small neutrino masses without small values of $\epsilon_3$ it is some times necessary to rely in cancelations between the two terms in eq. (3). In the next figures we see that this cancelation is not big enough to consider it a fine tuning. In addition, we study the effect of relaxing the universality at the GUT scale.
Figure 5. Regions in the $m_{\tilde{t}_1} - m_{\tilde{t}}$ plane where the Rp violating decay mode $\tilde{t}_1 \rightarrow b\tau$ is larger than 90%.

In Fig. 5 we have the ratio $\Gamma(\tilde{t}_1 \rightarrow b\tau)/\Gamma(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0)$ as a function of the neutrino mass. Large Rp violating branching ratios appear for large $\tan\beta$ and large values of $\epsilon_3$. Larger $\Gamma(\tilde{t}_1 \rightarrow b\tau)$ and smaller neutrino masses are obtained if we accept cancellations between the two terms in eq. (4). We do not think that cancellations up to four order of magnitude is a fine tuning, as it happens between vev’s in the MSSM with large values of $\tan\beta$. We have omitted from Fig. 5 points with large kinematical suppressions.

In Fig. 5 we imposed $m_{H_u}^2 = m_{H_d}^2$ at the GUT scale but not $B_3 = B$. The effect of imposing universality $B_3 = B$ at the GUT scale is to eliminate the points in the lower right corner in Fig. 5. The effect of not imposing the universality condition $m_{H_u}^2 = m_{H_d}^2$ at the GUT scale is more dramatic and is analyzed in the next figure.

In Fig. 5 we plot the neutrino mass as a function of the parameter $\sin\xi = v'_i/v'_1$ for $|\epsilon_3|/\mu = 1$ and the two values $\tan\beta = 3$ and 46, which translates into the nearly constant values $\Gamma(\tilde{t}_1 \rightarrow b\tau)/\Gamma(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0) = 2 \times 10^{-3}$ and 0.4 ± 0.2 respectively. We are accepting cancellations between the two terms in eq. (4) of only one order of magnitude. The minimum value of $m_{\nu_\tau}$ attainable in each case depends on the degree of non-universality. For $\tan\beta = 3$ tiny deviations from $m_{H_u}^2/m_{H_d}^2 = 1$ are enough to obtain neutrino masses of the order of eV. For $\tan\beta = 46$ larger deviations are necessary. We note that SUGRA models based on the $SO(10)$ gauge group with universality of Yukawa couplings, which need values of $\tan\beta \sim 45 - 55$, can produce the correct amount of non-universality from extra D-term contributions associated with the reduction in rank of the gauge symmetry group when spontaneously breaks to $SU(3) \times SU(2) \times U(1)$ [21].

In summary, the Bilinear R–Parity Violating extension of the MSSM can solve the atmospheric and solar neutrino problems by giving mass and mixing to the neutrinos through mixing with neutralinos. In this context, the Rp violating decay mode of the lightest stop $\tilde{t}_1 \rightarrow b\tau$ can dominate over the conventional modes introducing new signals that modify the search of stops in colliders.

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Figure 7. Allowed regions for $\Gamma(\tilde{\tau}_1 \rightarrow b\tau)/\Gamma(\tilde{\tau}_1 \rightarrow b\tilde{\chi}^0_1)$ as a function of the tau neutrino mass for different amounts of cancellation between the two terms that contribute to $m_{\nu_{\tau}}$. We consider $|\epsilon_3/\mu| = 1$ (inside the dashed lines), $|\epsilon_3/\mu| = 0.1$ (solid), and $|\epsilon_3/\mu| = 0.01$ (dotted).

REFERENCES

1. Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998).
2. J.C. Romão et al., hep-ph/9907499.
3. A. Faessler, S. Kovalenko, and F. Simkovic, JINR-E4-98-124 (May 1998); C.-H. Chang, and T.-F. Feng, hep-ph/9901260; D.E. Kaplan and A.E. Nelson, hep-ph/9901254; T. Feng, hep-ph/9806503.
4. M.A. Díaz, J. Ferrandis, J.C. Romão, and J.W.F. Valle, Phys. Lett. B 453, 263 (1999), and hep-ph/9906343; J. Ferrandis, hep-ph/9810371; M.A. Díaz, J. Ferrandis, and J.W.F. Valle, hep-ph/9909212.
5. M.A. Díaz, J.C. Romão, and J.W.F. Valle, Nucl. Phys. B 524, 23 (1998).
6. M. Hirsch and J.W.F. Valle, hep-ph/9812463.
7. R. Hempfling, Nucl. Phys. B 478, 3 (1996).
8. A.G. Akeroyd, M.A. Díaz, and J.W.F. Valle, Phys. Lett. B 441, 224 (1998).
9. M.A. Díaz and H.E. Haber, Phys. Rev. D 46, 3086 (1992).
10. ALEPH Collaboration, hep-ex/9908016.
11. ALEPH Coll., Eur. Phys. J. C2, 395 (1998).

Figure 8. Neutrino mass as a function of $\sin \xi = v_3'/v_1'$ and the effect of non-universality $m_{H_1}^2/m_{\tilde{L}_3}^2 \neq 1$ at the GUT scale.

12. A. Akeroyd et al., Nucl. Phys. B 529, 3 (1998).
13. M.A. Díaz, D.A. Restrepo, and J.W.F. Valle, hep-ph/9908280.
14. L. Navarro, W. Porod, J.W.F. Valle Phys. Lett. B 459, 615 (1999); F. de Campos et al., hep-ph/9903245.
15. M.A. Díaz and H.E. Haber, Phys. Rev. D 45, 4246 (1992).
16. CLEO Collaboration (M.S. Alam et al.), Phys. Rev. Lett. 74, 2885 (1995).
17. J.L. Hewett, Phys. Rev. Lett. 70, 1045 (1993); M.A. Diaz, Phys. Lett. B 304, 278 (1993) and Phys. Lett. B 322, 207 (1994); K. Chetyrkin, M. Misiak, and M. Münz, Phys. Lett. B 400, 206 (1997); M. Misiak, S. Pokorski, J. Rosicki, hep-ph/9703442.
18. M.A. Díaz, E. Torrente-Lujan, and J.W.F. Valle, Nucl. Phys. B 551, 78 (1999); E. Torrente-Lujan, hep-ph/9907220.
19. K.I. Hikasa and M. Kobayashi, Phys. Rev. D 36, 724 (1987).
20. M.A. Díaz, hep-ph/9905422 and hep-ph/9802407; J.W.F. Valle, hep-ph/9808292; J.C. Romão, hep-ph/9907464.
21. H. Baer et al., hep-ph/9907211; A. Datta et al., hep-ph/9907444.