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Correlation between neutrino oscillations and collider signals of supersymmetry in an R-parity violating model

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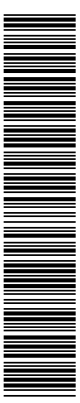
Abstract

Motivated by the recent Super-Kamiokande results on atmospheric neutrinos, we incorporate massive neutrinos, with large angle oscillation between the second and third generations, in a scenario with R-parity violating supersymmetry. We emphasize the testability of such models through the observation of comparable numbers of muons and taus, produced together with the W-boson, in decays of the lightest neutralino. A distinctly measurable decay gap is another remarkable feature of such a scenario.



The recent results from the Super-Kamiokande (SK) experiment on atmospheric neutrinos strengthen the already existing evidence in favour of neutrino oscillations [1]. The zenith angle distribution of the events can be explained assuming that ν_μ oscillates dominantly into ν_τ, or possibly into a sterile neutrino. A large mixing angle is strongly suggested by the data, with a best-fit mass-squared difference (Δm^2) of 2.2×10^{-3} eV^2. The Soudan-2 results support these claims, their favoured Δm^2 being above 1×10^{-3} eV^2 [2]. Further evidence comes from MACRO data on upward going muons [3]. Furthermore, oscillations of the above kind allow one to account for the solar neutrino flux deficit as well[4].

The very existence of mass and mixing in the neutrino sector takes one beyond the standard model, and the obvious question that arises is about a theoretical framework that naturally accommodates the observed data, particularly the large mixing angle. Several classes of models for neutrino masses exist in the literature, a few examples being see-saw models with massive right-handed neutrinos [5], models with radiative generation of neutrino masses [6], or Majorana masses induced by a Higgs triplet [7]. However, it requires considerable manoeuvring [8] in each of the above cases in order to achieve large angle oscillations while keeping everything else consistent from a phenomenological point of view.

An interesting possibility is supersymmetry (SUSY) [9] where non-zero neutrino masses can be envisioned once we allow the violation of R-parity, defined as $R = (-1)^{3B+L+2S}$ (where the baryon and lepton numbers B and L are assigned to the supermultiplets). This is in perfect consistence with all experimental observations, including proton stability, if either baryon or lepton number is still conserved. The standard way of writing down the R-parity violating effects [10] is to consider the following additional terms in the MSSM superpotential(suppressing SU(2) indices) :

$$W_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \epsilon_i L_i H_2 \qquad (1)$$

where, in a phenomenologically viable scenario, it is safe to either keep only the λ''-term or drop it. The λ and λ'-terms give rise to neutrino masses at the one-loop level; the bilinear terms $\epsilon_i L_i H_2$ in turn (in association with non-vanishing sneutrino vacuum expectation values) allow one to augment the neutralino mass matrix with the neutrinos, leading to a see-saw type mass for the latter. A number of studies on both possibilities have already been published [11, 12, 13, 14].

In this note, we are mainly concerned with the latter scenario for massive neutrinos, in the light of the current experimental indications on atmospheric neutrinos. We point out a logical way of understanding the observed results, which still keeps enough room for a solution of the solar neutrino puzzle. In doing this, we neither have to assume a near-equality of tree-and loop-induced masses [15], nor do we use only loop-induced effects [16] which run the risk of predicting an excess of flavour-changing neutral current (FCNC) phenomena. In our formulation, all extra parameters over and above the ones of MSSM can be traded by the neutrino mass-squared difference required by the SK data and the large angle of oscillation. And, most importantly, we predict that in a scenario like this, the decay of the lightest neutralino $\tilde{\chi}^0_1$ (which is unstable once R-parity is

violated) will produce comparable numbers of muons and taus as a result of large-angle mixing. This provides one with a method to test (or falsify) such models of neutrino mass generation in collider experiments.

We start by assuming bilinear terms in the superpotential (1) for $i = 2, 3$ only. Next, we rotate away the terms proportional to ϵ_2 and ϵ_3 by redefining the lepton and Higgs superfields. However, this does not eliminate the impact of the bilinear terms, since such rotation has its effect on the scalar potential [17], causing the sneutrinos to have non-vanishing vacuum expectation values (vev) in general. These vev's (denoted here by v_2 and v_3) induce terms in the neutralino mass matrix via the neutrino-sneutrino-Bino (or W_3-ino) interactions. Thus in this basis (which, for our purpose, serves as the flavour basis) the 6×6 neutralino mass matrix becomes

$$\mathcal{M} = \begin{pmatrix} 0 & -\mu & \frac{gv}{\sqrt{2}} & -\frac{g'v}{\sqrt{2}} & 0 & 0 \\ -\mu & 0 & -\frac{gv'}{\sqrt{2}} & \frac{g'v'}{\sqrt{2}} & 0 & 0 \\ \frac{gv}{\sqrt{2}} & -\frac{gv'}{\sqrt{2}} & M & 0 & -\frac{gv_3}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} \\ -\frac{g'v}{\sqrt{2}} & \frac{g'v'}{\sqrt{2}} & 0 & M' & \frac{g'v_3}{\sqrt{2}} & \frac{g'v_2}{\sqrt{2}} \\ 0 & 0 & -\frac{gv_3}{\sqrt{2}} & \frac{g'v_3}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -\frac{gv_2}{\sqrt{2}} & \frac{g'v_2}{\sqrt{2}} & 0 & 0 \end{pmatrix} \tag{2}$$

where the successive rows and columns correspond to $(\tilde{H}_2, \tilde{H}_1, -i\tilde{W}_3, -i\tilde{B}, \nu_\tau, \nu_\mu)$. Here

$$v \quad (v') = \sqrt{2} \left(\frac{m_Z^2}{\bar{g}^2} - \frac{v_2^2 + v_3^2}{2} \right)^{\frac{1}{2}} \sin\beta \quad (\cos\beta)$$

M and M' are the SU(2) and U(1) gaugino mass parameters respectively, μ, the Higgsino mass parameter, m_Z, the Z boson mass, and $\bar{g} = \sqrt{g^2 + g'^2}$. One can define two states ν_3 and ν_2, where

$$\nu_3 = \cos\theta \ \nu_\tau + \sin\theta \ \nu_\mu . \tag{3}$$

and ν_2 is the orthogonal combination, the neutrino mixing angle being

$$\cos\theta = \frac{v_3}{\sqrt{v_2^2 + v_3^2}}, \qquad \sin\theta = \frac{v_2}{\sqrt{v_2^2 + v_3^2}} \tag{4}$$

Clearly, the state ν_2 remains massless, whereas ν_3 acquires a see-saw type mass:

$$m_{\nu_3} \approx -\frac{\bar{g}^2(v_2^2 + v_3^2)}{2 \ \bar{M}} \times \frac{\bar{M}^2}{MM' - m_Z^2 \ \bar{M}/\mu \ \sin 2\beta} \tag{5}$$

where we introduced $\bar{g}^2\bar{M} = g^2M' + g'^2M$. The first term is very similar to the usual see-saw formula, with the only difference that couplings between the light and the heavy states is in the present case due to gauge interactions.

The massive state ν_3 can be naturally used to account for atmospheric neutrino oscillations, with $\Delta m^2 = m_{\nu_3}^2$. Large angle mixing between the ν_μ and the ν_τ corresponds to the situation where $v_2 \simeq v_3$. Before we discuss how this assumption affects the observable signatures for supersymmetry

at colliders, two remarks are in order:
1) The reason why only one neutrino becomes massive is that only one "heavy" state, the Zino, is coupled to the neutrinos (it corresponds to a see-saw formula in which only one right-handed neutrino has Yukawa couplings with the left-handed neutrinos).
2) The formalism can be extended to include a subdominant component ν_e of the massive neutrino state ν_3, simply letting the vev v_1 to be non-zero (future experimental data and analyses on neutrinos will permit us to assess the size of this component).

Let us now turn to the phenomenological implication of the above scenario in the neutralino sector. In most models, the lightest neutralino is the lightest supersymmetric particle (LSP). The non-conservation of R-parity implies that it can decay into particles with $R = +1$. Here, an interesting possibility arises exclusively from the bilinear R-violating terms [18, 19]. As a result of the mixing between neutrinos and neutralinos (as also between charged leptons and charginos) the LSP has the additional decay channels

$$\tilde{\chi}_1^0 \longrightarrow \nu_l Z \ (Z^*) \qquad l = e, \mu, \tau \tag{6}$$

and

$$\tilde{\chi}_1^0 \longrightarrow l W (W^*) \qquad l = e, \mu, \tau \tag{7}$$

which are absent with only the commonly discussed λ-and λ'- terms at leading order. However, if the neutralino is lighter than the W boson, then the resulting three-body decays give rise to final states which can also be produced by the trilinear R-violating interactions. Thus, the signals for bilinear interactions are most prominent for $m_{\tilde{\chi}_1^0} > m_Z (m_W)$, which corresponds to a large part of the SUSY parameter space still allowed by experiments.

In the above range of neutralino masses, large angle mixing between the second and third neutrino generations implies that l in Eqn.(7) above can be the muon or the tau with comparable probabilities. Thus one should see muons and tau's in near-equal numbers, along with the W-boson, in the collider signals of the lightest neutralino if R-parity violating SUSY has to provide the mechanism of generating neutrino masses.

In Fig.(1), we plot the branching ratios of the two-body decays as functions of the neutralino mass. We demonstrate our point by assuming maximal mixing, i.e. $\theta = \pi/4$, which is achieved by setting $v_2 = v_3$. In our calculation, the MSSM parameters μ, $\tan\beta$ and the universal gaugino mass $\tilde{M}$ are used as the input parameters. The gaugino mass parameters M and M' have been assumed to be related by the condition of (SU(5)) gaugino mass unification.

In our plot, both $l^+ W^-$ and $l^- W^+$ $(l = \mu, \tau)$ have been included in the charged current decay modes. We have checked that the relative strengths of the W-and Z-modes (which flatten out once the phase space suppressions become insignificant) remain roughly the same and insensitive to μ and $\tan\beta$ so long as the LSP continues to be dominated by the Bino. The ratio between the two types of decays can change when there is a substantial Higgsino content of the LSP, which can

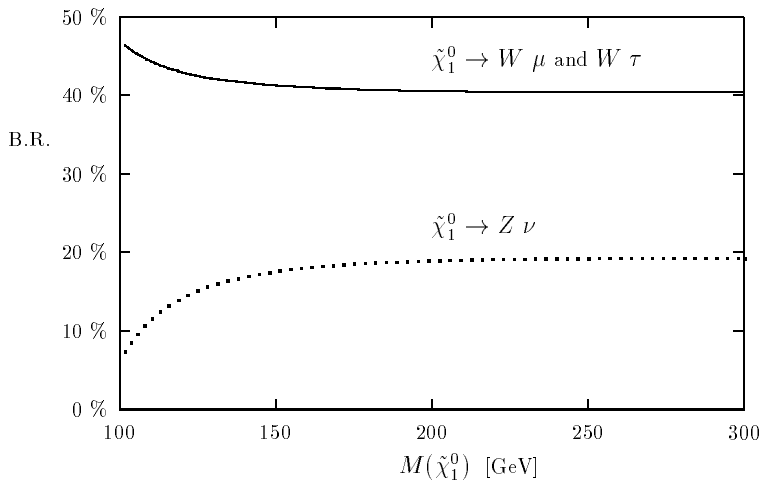


Figure 1: Branching ratio for the decay channels of the lightest supersymmetric state $\tilde{\chi}_1^0$. The neutrino mixing angle is maximal, and $\Delta m^2 = 2.15 \times 10^{-3}$ eV^2. The remaining supersymmetric parameters are chosen as: $\mu = -500$ GeV, $\tan\beta = 5$.

consequently have couplings with the W and the Z. Also, here we have neglected the two-body decay of the LSP with the lightest Higgs boson in the final state. The latter can be appreciable (up to about 25% [19]) when the LSP has a large Higgsino component, or when it is Bino-dominated and $\tan\beta$ is close to 1. However, none of the above situations alter the fact that muons and taus are produced in comparable intensities as a result of neutralino decay, so long as the neutralino is massive enough for the two-body decays to be allowed. Therefore, our main prediction continues to hold over the entire $\mu - \tan\beta$ space consistent with experiments.

Another useful test for this scenario can be performed by measuring the decay length of the lightest neutralino. This is given by the formula

$$L = \frac{\hbar}{\Gamma} \times \frac{p}{M(\tilde{\chi}_1^0)} \tag{8}$$

where Γ is the decay width of the lightest neutralino and p its momentum. In Fig. 2 we present a plot of the decay length against the neutralino mass for three different values of Δm^2, corresponding to the extreme limits allowed by SK data for $\nu_\mu \to \nu_\tau$ oscillation. The decaying neutralino is assumed to have an energy of 250 GeV. As is expected, the decay length decreases for higher neutrino masses, as a result of the enhanced probability of the flip between Bino and neutrinos, when the LSP is dominated by the Bino. What is interesting, however, is the fact that the decay lengths are as large as about 0.1 - 10 millimeters even for the largest possible neutrino mass. This gives us an additional and rather interesting characterization of the reaction $\tilde{\chi}^0 \longrightarrow \tau(\mu)W$ at colliders, in the assumption that these states are sufficiently light to be produced in next colliders.

Finally we consider the question of what effects do the trilinear R-violating couplings λ, λ' have on our scenario. Their presence will in general give rise to mass terms, both diagonal and off-

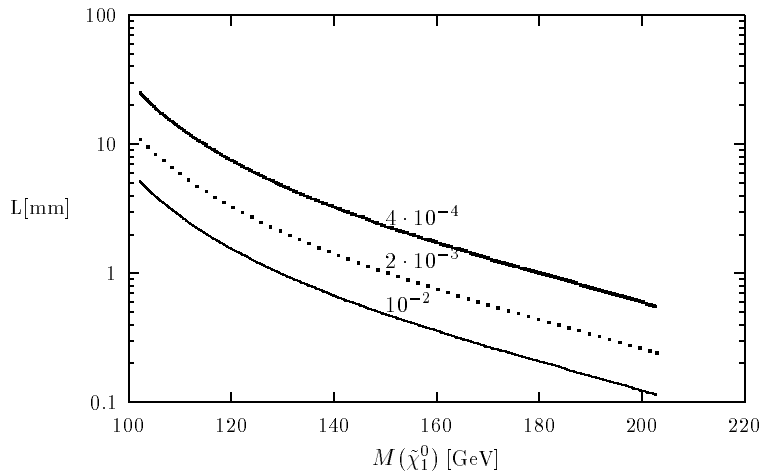


Figure 2: Decay length for $\tilde{\chi}_1^0$ for three values of Δm^2, indicated at the curves. $\mu = -500$ GeV, $\tan\beta = 5$.

diagonal, generated at one-loop level involving all the neutrinos. The general expression for these masses is

$$(m_\nu^{loop})_{ij} \simeq \frac{3}{8\pi^2} m_k^d m_p^d M_{SUSY} \frac{1}{m_{\tilde{q}}^2} \lambda'_{ikp}\lambda'_{jpk} + \frac{1}{8\pi^2} m_k^l m_p^l M_{SUSY} \frac{1}{m_{\tilde{l}}^2} \lambda_{ikp}\lambda_{jpk} \qquad (9)$$

where $m^{d,l}$ denote the down-type quark and charged lepton masses, respectively. $m_{\tilde{l}}^2$, $m_{\tilde{q}}^2$ are the slepton and squark mass squared. $M_{SUSY}(\sim \mu)$ is the effective scale of supersymmetry breaking. If we want the mass thus induced for the second generation neutrino to be the right one to solve the solar neutrino problem, then one obtains some constraint on the value of the λ's as well as λs. In order to generate a splitting between the two residual massless neutrinos, $\delta m^2 \simeq 5 \times 10^{-6}$ eV^2 (which is suggested for an MSW solution [20]), a SUSY breaking mass of about 500 GeV implies $\lambda'\,(\lambda) \sim 10^{-4} - 10^{-5}$. Such a value of $\lambda'\,(\lambda)$ makes the three-body decays of the neutralino too small compared to the two-body decays when they are allowed. The mass-squared difference required for a vacuum oscillation solution [21] to the solar puzzle requires even smaller values of $\lambda'(\lambda)$. Thus the simultaneous presence of trilinear and bilinear R-violating couplings are not expected to cause any noticeable change in the muon vs. tau branching ratios in LSP decays that we are concerned with.

In conclusion, we have discussed an R-parity violating scenario which can accommodate the large mixing angle suggested by the atmospheric neutrino anomaly. The signature of this scenario is the production of comparable numbers of muons and tau's in the decay of the lightest neutralino at colliders. In addition, the decay could lead to a measurable secondary vertex (decay gap). This provides one with the prospect of a verification in collider experiments as to whether SUSY indeed is responsible for the masses and mixing of neutrinos.

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