

Neutrino masses and mixing in a supersymmetric model and characteristic signatures at the LHC

Pradipta Ghosh* and Sourov Roy†

*Department of Theoretical Physics and Centre for Theoretical Sciences,
Indian Association for the Cultivation of Science,
2A & 2B Raja S.C. Mullick Road, Kolkata 700 032, India*

The experimental results on neutrinos provide evidence of non-zero neutrino masses and mixing angles. In this work we examine in detail the neutrino mass patterns and mixing angles in an extension of the minimal supersymmetric standard model with three gauge-singlet neutrinos and R-parity violation. The Majorana masses for the gauge-singlet neutrinos as well as the usual μ -term for the Higgs Superfields are generated at the electroweak scale through the vacuum expectation values of the singlet δ neutrinos. The resulting effective mass matrix for the three light neutrinos have contributions from the seesaw mechanism involving the singlet neutrinos as well as due to the mixing with the heavy neutralinos. We show that even with flavour diagonal neutrino Yukawa couplings the global data on three-flavour neutrinos can be well accounted for in this scenario at the tree level. We further study the decays of the lightest neutralino in this model. The lightest neutralino can be the lightest supersymmetric particle (LSP). We focus on different cases where the lightest neutralino is either a bino or a higgsino or a gauge-singlet neutrino. We study the important phenomenological differences between these cases and find out that certain ratios of decay branching ratios of the lightest neutralino are correlated with either the solar or the atmospheric (and reactor) neutrino angle.

Neutrino oscillation experiments have confirmed nonzero masses and mixing-angles for neutrinos. Various experiments suggest that the mixing pattern of the three light neutrinos is bilarge, that is to say there are two large mixing angles and one small mixing angle. The data can be explained very well with the following set of mass squared differences and mixing angles at 3σ C.L. [1]

$$\begin{aligned} 7.05 \times 10^{-5} \text{eV}^2 &\leq \Delta m_{21}^2 \leq 8.34 \times 10^{-5} \text{eV}^2, \\ 2.07 \times 10^{-3} \text{eV}^2 &\leq \Delta |m_{31}^2| \leq 2.75 \times 10^{-3} \text{eV}^2, \\ 30.39^\circ &\leq \theta_{12} \leq 37.46^\circ, \quad 36.87^\circ \leq \theta_{23} \leq 54.94^\circ, \\ \theta_{13} &\leq 13.69^\circ, \end{aligned} \quad (1)$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.

In order to explain the results in Eq.(1) one needs to go to a theory beyond the standard model (SM). Supersymmetry(SUSY) is an interesting possibility for new physics at TeV scale. There have been several proposals in recent times which attempt to explain the experimental data on neutrinos in the context of minimal supersymmetric standard model (MSSM) with bilinear and trilinear R-parity violation [2–4]. Due to R-parity violation the lightest superparticle (LSP) is unstable for this class of models.

However MSSM possesses the so-called “ μ -problem” [5], related to the bilinear term $\mu \hat{H}_1 \hat{H}_2$ in the MSSM superpotential. One of the solutions to

the “ μ -problem” is the next-to-minimal supersymmetric standard model (NMSSM), where an effective μ term gets generated through the vacuum expectation value (VEV) of some superfield $\hat{S}$, singlet under the SM gauge group. However, as in the case of R-parity conserving MSSM, the R-parity conserving NMSSM also cannot explain the observed pattern of neutrino masses and mixing.

Generation of neutrino masses and mixings in the context of R-parity violating NMSSM have been addressed in the Refs.[6–8]. In this work we study a model of neutrino masses and mixing which introduces the gauge singlet neutrino superfields $\hat{\nu}_i^c$ to solve the μ problem. We show that it is possible to accommodate small neutrino masses and bilarge mixing explaining the experimental data, with flavour diagonal neutrino Yukawa coupling matrix. We show that the three flavor neutrino data can be accommodated in such a scenario for different neutrino mass hierarchies (normal and inverted) even at the tree level.

The superpotential of the model is written as

$$W = \epsilon_{ab}(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c + Y_\nu^{ij} \hat{H}_2^b \hat{L}_i^a \hat{\nu}_j^c) - \epsilon_{ab} \lambda^i \hat{\nu}_i^c \hat{H}_1^a \hat{H}_2^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c, \quad (2)$$

where $\hat{H}_1^T = (\hat{H}_1^0, \hat{H}_1^-)$, $\hat{H}_2^T = (\hat{H}_2^+, \hat{H}_2^0)$, $\hat{Q}_i^T = (\hat{u}_i, \hat{d}_i)$, $\hat{L}_i^T = (\hat{\nu}_i, \hat{e}_i)$, a, b are $SU(2)$ indices, and $\epsilon_{12} = 1$.

The last two terms in (2) explicitly breaks lepton number (L) and hence the R-parity, which is defined as $R = (-1)^{L+3B+2s}$. Here B is the baryon number and s is the spin. Note that $R = +1(-1)$ for particles (superpartners). The fourth term in the superpotential involving the neutrino Yukawa couplings, generates effective bilinear R-parity violating interactions $\epsilon^i \hat{A}_2 \hat{L}_i$. Here ϵ^i is determined in terms of the VEVs of right-handed sneutrinos $\hat{\nu}_i^c$ (see Eq.(3)) and is given by $\epsilon^i = Y_\nu^{ij} \hat{\nu}_j^c$. Finally one should note that the superpotential has a discrete Z_3 symmetry, as in the case of NMSSM,

which when spontaneously broken in the vacuum, might lead to cosmological domain wall problem [9]. However, the solutions to this problem exist [10] and will also work in this case.

In this model, mixing between neutral Higgs bosons with the Sneutrinos, charged Higgs bosons with the charged Sleptons enhances the corresponding scalar, pseudoscalar and charged scalar mass squared matrices. Similarly neutralino-neutrino mixing and chargino-charged leptons mixing enhances the neutralino and chargino mass matrices. Because of the mixing between the neutralinos and the neutrinos, the lightest neutralino ($\tilde{\chi}_1^0$), which is the lightest superparticle (LSP) for most of the parameter space, can have novel decay modes which can be correlated with the neutrino mixing pattern. This can provide some unique signatures of such a scenario which can be tested at the LHC. This model has been named as the “ $\mu\nu$ SSM” in Ref.[11].

We would like to emphasize here that our analysis shows that even with flavor diagonal neutrino Yukawa couplings, the resulting structure of the effective mass matrix of the light neutrinos can explain the bilarge pattern of mixing. In addition, we explore the correlation between the neutrino mixing and the decay pattern of the LSP in this model and discuss some other interesting phenomenological implications.

Once the electroweak symmetry is spontaneously broken, the neutral scalars develop in general the following VEVs:

$$\langle H_1^0 \rangle = v_1, \quad \langle H_2^0 \rangle = v_2, \quad \langle \tilde{\nu}_i \rangle = \nu_i, \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c. \quad (3)$$

One can check that in the limit $Y_\nu^{ij} \rightarrow 0$, minimization equation for left-handed sneutrino implies $\nu_i \rightarrow 0$. Since the coupling Y_i determines the Dirac mass for the neutrinos, $m_D \equiv Y_\nu v_2$, ν_i has to be very small. Smallness of left handed sneutrino VEV (i.e. $\nu_i \ll v_1, v_2$) still allow us to use the following assumption without any loss of generality

Electronic address: tppg@iacs.res.in

Electronic address: tpsr@iacs.res.in

$$m_Z^2 \approx \frac{1}{2}(g_1^2 + g_2^2)(v_1^2 + v_2^2), \quad \tan \beta \approx \frac{v_2}{v_1}. \quad (4)$$

When lepton-number violation is allowed, the light neutrino mass matrix arising via the seesaw mechanism is in general given by

$$M_{3 \times 3}^\nu = -m_{3 \times 7} M_{7 \times 7}^{-1} m_{3 \times 7}^T, \quad (5)$$

where $m_{3 \times 7}$ is the so-called Dirac neutrino mass matrix. $M_{7 \times 7}$ is the matrix for the heavy states and contains $\Delta L = 2$ mass terms for right-handed neutrinos. There are also mixing terms between these states. This is because the superpotential (2) used here admits neutrino-neutralino mixing. Thus three right handed neutrinos together with four MSSM neutralino states give the 7×7 matrix $M_{7 \times 7}$. On the other hand $m_{3 \times 7}$ includes the Dirac mass terms $\bar{\nu}_L \nu_R^c$ as well as neutrino-neutralino mixing terms.

With several simplified assumptions, an approximate analytical expression for the 3×3 effective neutrino mass matrix is given by

$$M_{ij}^\nu \approx \frac{1}{6\kappa\nu^c} a_i a_j (1 - 3\delta_{ij}) + \frac{2A\nu^c}{3\Delta} b_i b_j, \quad (6)$$

where

$$A = (\kappa\nu^c + \lambda v_1 v_2), \quad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2},$$

$$\Delta = \lambda^2 (v_1^2 + v_2^2)^2 + 4\lambda\kappa\nu^c v_1 v_2 - 4MA\lambda\mu,$$

$$a_i = Y_\nu^{ii} v_2, \quad b_i = (Y_\nu^{ii} v_1 + 3\lambda\nu_i), \quad \mu = 3\lambda\nu^c. \quad (7)$$

Here i, j, k are generational indices, $M_1(M_2)$ is the gaugino soft mass parameter for $U(1)(SU(2))$ sector and $g1(g2)$ is the corresponding gauge coupling.

Comparison of masses and mixing angles as obtained from the approximate analytical formulae and from full numerical calculation shows good agreement. As an example, the atmospheric neutrino mixing angle θ_{23} is given by $\tan^2 \theta_{23} = \frac{b_\mu^2}{b_\nu^2}$. Comparison of the neutrino mass eigenvalues as obtained from approximate analytical formulae and full numerical calculation using Eq.(5) are shown in Table I.

m_ν (eV)	$m_1 \times 10^3$	$m_2 \times 10^3$	$m_3 \times 10^2$
Using Eq.(5)	5.166	9.878	4.629
approximate calculation	5.145	9.439	4.583

TABLE I: Comparison of neutrino masses as obtained from full numerical calculation and from approximate analytical calculation.

As mentioned earlier, the lightest supersymmetric particle is unstable due to R-parity violation. The lightest neutralino ($\tilde{\chi}_1^0$) can be the LSP with a predominantly bino or higgsino component. For suitable parameter choices $\tilde{\chi}_1^0$ can also be right-handed neutrino dominated. However, with a right-handed neutrino dominated $\tilde{\chi}_1^0$, right-handed sneutrino is the LSP.

We study R-parity violating two-body decays of $\tilde{\chi}_1^0$ into charged lepton (l_i) + W pair and into neutrino (ν_i) + Z pair. $\tilde{\chi}_1^0$ was assumed to be with either preponderant bino component or with preponderant higgsino or righthanded neutrino component. We also calculated the decay branching ratios for $\tilde{\chi}_1^0 \rightarrow l_i W$ and $\tilde{\chi}_1^0 \rightarrow \nu_i W$ processes. We observe nice correlations of the neutrino mixing angles with the ratios of decay branching ratios for $\tilde{\chi}_1^0 \rightarrow l_i W$ processes. We performed this study for both normal and inverted mass pattern of neutrinos and study the variations among different scenarios. Presence of these correlations suggests that present experimental limits on the neutrino mixing angles can put bounds on the ratios of decay branching ratios for $\tilde{\chi}_1^0 \rightarrow l_i W$ processes. Thus this model is testable at the upcoming future colliders.

To summarize, we have studied a model where right handed neutrino was introduced to solve the μ -problem and to generate non-vanishing neutrino masses and mixing angles satisfying present experimental bounds. We have also calculated the R-parity violating two-body decays of the lightest neutralino (which may or may not be the LSP). We studied the correlations between the ratios of decay branching ratios for $\tilde{\chi}_1^0 \rightarrow l_i W$ processes and the neutrino mixing angles.

R-parity violation makes the phenomenology of this model very distinct and rich from other models. Therefore it will be interesting to study various characteristic collider signatures of this model in the upcoming LHC. A detail study of production and decay mechanism for right-handed neutrino dominated $\tilde{\chi}_1^0$ will be very interesting in the context of future collider experiments. Investigating the decay products of a right-handed neutrino dominated $\tilde{\chi}_1^0$, one can also probe the right-handed neutrino mass scale in collider experiments.

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