Lepton-Flavour Violation in SUSY with and without R–parity

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We study whether the individual violation of the lepton numbers $L_{e,\mu,\tau}$ in the charged sector can lead to measurable rates for $BR(\mu \rightarrow e\gamma)$ and $BR(\tau \rightarrow \mu\gamma)$. We consider three different scenarios, the fist one corresponds to the Minimal Supersymmetric Standard Model with non–universal soft terms. In the other two cases the violation of flavor in the leptonic charged sector is associated to the neutrino problem in models with a see–saw mechanism and with R–parity violation respectively.

1 Introduction

In the Standard Model (SM), lepton number is exactly preserved in contradiction with the observed neutrino oscillations [1, 2]. Typically, enlargements of the SM explaining these flavor oscillations include violation of the lepton numbers $L_{e,\mu,\tau}$ for charged lepton which will be manifested in processes such as $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu - e$ conversion in heavy nuclei, $\tau \rightarrow \mu\gamma$ and $K_L \rightarrow \mu e$. The experimental upper bound for these processes is quite restrictive, which imposes a significant constraint for the explanation of flavor in models beyond the SM. The Supersymmetric extension of the SM (SUSY) provides an excellent framework to study them, since the predicted rates can be of the order of the bounds that will be reached in current or projected experiments. In addition the SUSY contribution to the anomalous magnetic moment of the muon, $a_\mu \sim (g_\mu - 2)/2$ can be compatible with the difference between the value predicted by the SM and the recent measured value [3].

In this presentation we concentrate on the study of $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$, their current experimental limits are [4]:

$$BR(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$$
$$BR(\tau \rightarrow \mu\gamma) < 1.1 \times 10^{-6}.$$  \hspace{1cm} (1)

The SUSY predictions for these processes will be shown in three different scenarios. The first is Minimal Supersymmetric SM (MSSM) with non–universal soft–terms [5], without

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Results for other processes like $\mu - e$ conversion in heavy nuclei and $K_L \to \mu e$ can be found in refs. [6, 8, 9] and references there in.

2 $l_j \to l_i \gamma$ Flavor Violating Processes and the $\mu$ Anomalous Magnetic Moment

The effective operators that generate the decays $l_j^- \to l_i^- \gamma$ and the lepton anomalous magnetic moment can be written as:

$$L_{\text{eff}} = e \frac{m_{l_j}}{2} l_j^\dagger \sigma_{\mu\nu} F^{\mu\nu} \left( A_{Lij} P_L + A_{Rij} P_R \right) l_j$$

(2)

The one–loop contributions to $A_{L,R}$ in R–parity conserving SUSY arises from the diagrams in Fig. 1, while for models with BRpV the corresponding diagrams are presented in Fig. 4.

The branching ratio for the rare lepton decays $l_j \to l_i \gamma$ is given by [10]:

$$BR(l_j^- \to l_i^- \gamma) = \frac{48\pi^3\alpha}{G_F^2} \left( |A_{Lij}|^2 + |A_{Rij}|^2 \right).$$

(3)

The expression for the muon anomalous magnetic moment can be obtained from the Lagrangian given in Eq. (2):

$$a^\mu = \frac{(g^\mu - 2)}{2} = -m^2_{\mu}(A^\mu_{L} + A^\mu_{R})$$

(4)

In R–parity conserving SUSY models, the presence of LFV processes is associated with vertexes involving leptons and their superpartners. In the Minimal Supersymmetric Standard Model (MSSM), with universal soft terms, it is possible to rotate the charged lepton Yukawa couplings and the sleptons in such a way that lepton flavor is preserved. However, a small deviation from flavor universality in the soft-terms at the GUT scale will be severely constrained by the experimental bounds [1]. In fact GUT theories

Figure 1: Generic Feynman diagrams for $\mu \to e\gamma$ decay: $\tilde{l}$ represents a charged slepton (a) or sneutrino (b), and $\tilde{\chi}^{(n)}$ and $\tilde{\chi}^{(c)}$ represent neutralinos and charginos respectively.
and models with $U(1)$ family symmetries can lead to the MSSM with flavor-dependent soft terms leading to important violations of the lepton flavor.

The lepton Yukawa couplings can be diagonalized by the unitary matrices $U_L$ and $U_R$ as follows,

$$m_l = \frac{v \cos \beta}{\sqrt{2}} U_R (Y_l)^T U_L^\dagger.$$  

(5)

When the superfields are written in this basis, the expressions for the charged slepton mass matrices at low energy take the form:

$$M_i^2 = \begin{pmatrix} \left( M_i^2 \right)_{LL} & \left( M_i^2 \right)_{LR} \\ \left( M_i^2 \right)_{RL} & \left( M_i^2 \right)_{RR} \end{pmatrix},$$  

(6)

where,

$$(M^2_{i})_{LL} = U_L m^2_L U_L^\dagger + m_i^2 - \frac{m_Z^2}{2} (1 - 2 \sin^2 \theta_W) \cos 2\beta,$$

$$(M^2_{i})_{RR} = U_R (m^2_R)^T U_R^\dagger + m_i^2 + m_Z^2 \sin^2 \theta_W \cos 2\beta,$$

$$(M^2_{i})_{LR} = (M^2_{i})^\dagger_{RL} = -\mu m_l \tan \beta + \frac{v \cos \beta}{\sqrt{2}} U_L Y_A^* U_R^\dagger,$$

(7)

where $m^2_L$ and $m^2_R$ are the soft breaking $(3 \times 3)$ mass matrices for the slepton doublet and singlet respectively.

The sneutrino mass matrix is simply given by the $(3 \times 3)$ mass matrix:

$$M_\tilde{\nu}^2 = U_L m^2_L U_L^\dagger + \frac{m_Z^2}{2} \cos 2\beta.$$  

(8)

The relevant lepton–flavor changing mass matrix elements on the slepton mass matrices above are given by:

$$\left( \delta^i_{LL} \right)_{ij} = \left[ U_L \ m^2_L \ U_L^\dagger \right]_{ij}$$

$$\left( \delta^i_{LR} \right)_{ij} = \left[ U_L \ Y_A^* \ U_R^\dagger \right]_{ij}$$

$$\left( \delta^i_{RR} \right)_{ij} = \left[ U_R \ (m^2_R)^T \ U_R^\dagger \right]_{ij}$$

(9)

where $i, j$ are flavor indices ($i \neq j$).

### 3 Models with Non-universal Soft SUSY breaking terms

The example of the MSSM with non-universal soft SUSY breaking terms presented here is based on the effective supergravity theories which emerge in the low energy limit of the weakly coupled heterotic strings (WCHS).
In the WCHS, it is assumed that the superpotential of the dilaton \((S)\) and moduli \((T)\) fields is generated by some non-perturbative mechanism, and that the \(F\)-terms of \(S\) and \(T\) contribute to the SUSY breaking. Hence one can parametrize the \(F\)-terms as

\[
F^S = \sqrt{3}m_{3/2}(S + S^*) \sin \theta, \quad F^T = m_{3/2}(T + T^*) \cos \theta. \tag{10}
\]

Here \(m_{3/2}\) is the gravitino mass and \(\tan \theta\) corresponds to the ratio between the \(F\)-terms of \(S\) and \(T\). In this framework, the soft scalar masses \(m_i\) and the gaugino masses \(M_a\) are given by

\[
m_i^2 = m_{3/2}^2(1 + n_i \cos^2 \theta), \quad M_a = \sqrt{3}m_{3/2} \sin \theta, \tag{11, 12}
\]

where \(n_i\) is the modular weight of the corresponding field. The \(A\)-terms are written as

\[
A_{ijk} = -\sqrt{3}m_{3/2} \sin \theta - m_{3/2} \cos \theta(3 + n_i + n_j + n_k), \tag{13}
\]

where \(n_{i,j,k}\) are the modular weights of the fields that are coupled by this \(A\)-term. We assume \(n_i = -2\) for the first two generations and for the down Higgs and \(n_i = -1\) for the third generation and the up Higgs.

To illustrate the dependence of the results on the lepton Yukawa couplings, we consider two examples of symmetric textures at the GUT scale:

- **Texture I**, \(Y_l = y^\tau \begin{pmatrix} 0 & 5.07 \times 10^{-3} & 0 \\ 5.07 \times 10^{-3} & 8.37 \times 10^{-2} & 0.4 \\ 0 & 0.4 & 1 \end{pmatrix} \) \tag{14}

- **Texture II**, \(Y_l = y^\tau \begin{pmatrix} 3.3 \times 10^{-4} & 1.64 \times 10^{-5} & 0 \\ 1.64 \times 10^{-5} & 8.55 \times 10^{-2} & 0.4 \\ 0 & 0.4 & 1 \end{pmatrix} \) \tag{15}

Texture I is a symmetric texture which can be considered to be the limiting case of textures arising from \(U(1)\) family symmetries as described in Refs. \([14]\) and studied in the next section. Typically a prediction for the decay \(\tau \rightarrow \mu \gamma\) of the order of the experimental limit \((1)\) will imply a severe violation of the experimental bound for \(\mu \rightarrow e \gamma\). We can see in Fig. 2 how texture I (graphic on the left) tolerates small deviations from universality of the soft terms. The experimental bound on \(BR(\mu \rightarrow e \gamma)\) is satisfied only for \(\sin \theta > .96\) \((m_{3/2} = 200 \text{ GeV})\) and for \(\sin \theta > .91\) \((m_{3/2} = 400 \text{ GeV})\) while for the same range on \(\sin \theta\) the corresponding prediction for \(BR(\tau \rightarrow \mu \gamma)\) is well below the experimental bound.

Texture II was chosen as an illustration of how the current bounds \((1)\) can provide some information about the lepton Yukawa couplings on the context of the models considered. The results obtained using texture II (Fig. 2, graphic on the right) allow us to start the graph at the lowest value of \(\sin \theta = 1/\sqrt{2}\). As it can be seen, the experimental bounds are more restrictive for the \(\tau \rightarrow \mu \gamma\) than for \(\mu \rightarrow e \gamma\) process.
4 SUSY Models with "see-saw" Mechanism

One of most attractive mechanisms for obtaining sub-eV neutrino masses is the "see-saw" mechanism \cite{15}. The "see-saw" mechanism can be included in SUSY models by enlarging the MSSM with right-handed neutral fields, $N^c$, such that the superpotential at the GUT scale becomes:

$$ W = W_{MSSM} + N^c h_D L H_u + \lambda_N N^c N^c; \quad (16) $$

Were $\chi$ is a singlet field which acquires a VEV at a high scale of energy leading to heavy Majorana masses for the fields $N^c$, $M_N = \lambda_N < \chi >$.

The effective theory below the $M_N$ \cite{10,16} scale (which here is assumed common for the three generations) is the the MSSM with tiny neutrino masses:

$$ W_{eff} = W_{MSSM} + (h_D L H_u)^T M_N^{-1} (h_D L H_u); \quad (17) $$

In general, the Dirac neutrino and charged-lepton Yukawa couplings, $h_D$ and $Y_l$ respectively, cannot be diagonalized simultaneously. Since both these sets of lepton Yukawa couplings appear in the renormalization-group equations, the lepton Yukawa matrices and the slepton mass matrices cannot be diagonalized simultaneously at low energies, either. In the basis where $Y_l$ is diagonal, the slepton-mass matrix acquires non-diagonal contributions from renormalization at scales below $M_{GUT}$ \cite{16}, of the form:

$$ (\delta_{LL}) \propto \frac{1}{16\pi^2} (3 + a^2) \ln \frac{M_{GUT}}{M_N} h_D^T h_D m_{3/2}^2, \quad (18) $$

where $a$ is related to the trilinear mass parameter: $A_{\ell} \equiv a m_0$, where $m_0$ is the common assumed value of the scalar masses at the GUT scale.
Figure 3: The contours BR($\mu \rightarrow e\gamma$) = $10^{-11}, 10^{-12}, 10^{-13}$ and $10^{-14}$ are shown as dash-dotted black lines in the ($m_{1/2}, m_0$) planes for $\mu > 0$ and $\tan \beta = 30$. Other constraints in these planes are taken from [17], assuming $A_0 = 0, m_t = 175$ GeV and $m_b(m_b)_{\overline{MS}} = 4.25$ GeV. The region allowed by the E821 measurement of $a_\mu$ at the 2-$\sigma$ level is the area on the right of the solid black line. The dark (red) shaded regions are excluded because the LSP is the charged $\tilde{\tau}_1$, and the light (gray) shaded regions are those with $0.1 \leq \Omega_\chi h^2 \leq 0.3$ that are preferred by cosmology. We show the contours $m_h = 113, 117$ GeV. The medium (green) shaded regions are excluded by $b \rightarrow s\gamma$.

In order to illustrate our estimates of the expected effects, we calculate the rates for rare processes violating charged-lepton number in a model with Abelian flavor symmetries and symmetric fermion mass matrices [14], which leads to the following pattern of charged-lepton masses $m_\ell$ and neutrino Dirac masses $m_{\nu D}$:

$$m_\ell \propto \begin{pmatrix} \overline{\tau}^7 & \overline{\tau}^3 & \overline{\tau}^{7/2} \\ \overline{\tau}^3 & \overline{\tau} & \overline{\tau}^{1/2} \\ \overline{\tau}^{7/2} & \overline{\tau}^{1/2} & 1 \end{pmatrix}, m_{\nu D} \propto \begin{pmatrix} \overline{\tau}^1 & \overline{\tau}^6 & \overline{\tau}^7 \\ \overline{\tau}^6 & \overline{\tau}^2 & \overline{\tau} \\ \overline{\tau}^7 & \overline{\tau} & 1 \end{pmatrix},$$

(19)

where $\overline{\tau}$ is a (small) expansion parameter related to the Abelian symmetry-breaking scale (assumed here to be $\approx 0.2$).

The elements of the Yukawa coupling matrices at the GUT scale can be chosen to be consistent with the experimental values of the fermion masses by introducing coefficients of order one in the entries of the mass matrices. In the notation of [8], we choose for this model (model A) $C_{12} = 0.77, C_{23} = 0.79$.

The difference on the value of the muon anomalous magnetic moment found in the BNL E821 measurement [3] with respect to the SM prediction, which originally was considered to be 2.6 $\sigma$ is now reduced to 1.6 $\sigma$ after a theoretical error has been corrected (see discussion and references in [8]). When the 2 $\sigma$ range is considered, the allowed values for contributions beyond the SM become,

$$-6 \times 10^{-10} \leq \delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \leq 58 \times 10^{-10},$$

(20)
The predictions for $BR(\mu \to e\gamma)$ are shown in Fig. 3, the solid line correspond to the upper bound of (20). The other constraints described in the caption are taken from [17]. The predictions for $B(\tau \to \mu\gamma)$ in this model can be found in [8], these are typically less restrictive than the case of $\mu \to e\gamma$ discussed above.

5 SUSY with Bilinear R–Parity Violation

The simplest extension of the MSSM with bilinear R–parity violation (BRpV) (allowing B–conserving but L-violating interactions) can explain the neutrino masses and mixings which can account for the observed neutrino oscillations [18].

In the model we consider, the MSSM superpotential is enlarged with bilinear terms that violate lepton number and therefore also breaks R–parity:

$$W = W_{MSSM} + \epsilon_i L_i H_u.$$  \hfill (21)

The inclusion of the R–parity violating term, though small, can modify the predictions of the MSSM. The most salient features are that neutrinos become massive and the lightest neutralino is no longer a dark matter candidate because it is allowed to decay. Furthermore, we can observe that this model implies the mixing of the leptons with the usual charginos and neutralinos of the MSSM. Lepton Yukawa couplings can be written as diagonal matrices without any loss of generality since it is possible to rotate the superfields $L_i$ in the superpotential, Eq. (21), such that Yukawa matrix $Y_l$ becomes diagonal. Conversely, in BRpV models it is possible to apply a similar rotation to reduce the number $\epsilon$ parameters and provide a non-trivial structure to $Y_l$ [19].

In addition to the MSSM soft SUSY breaking terms in $V_{soft}^{MSSM}$ the BRpV model contains the following extra term

$$V_{soft}^{BRpV} = -B_i \epsilon_i \bar{L}_i H_u.$$  \hfill (22)

The electroweak symmetry is broken when the two Higgs doublets $H_d$ and $H_u$, and the neutral component of the slepton doublets $\tilde{L}_i$ acquire vacuum expectation values.

In addition to the above MSSM parameters, our model contains nine new parameters, $\epsilon_i$, $v_i$ and $B_i$. The minimization of the scalar potential allows to relate some of these free parameters.

The range of values of the $\epsilon$–parameters is indirectly associated to the size of the neutrino masses predicted by the model. To explore this relation we describe next the mass mixings among neutralinos and neutrinos. In the basis $\psi^0 = (\bar{\lambda}', -i\lambda^3, \bar{H}_d^0, \bar{H}_u, \nu_e, \nu_\mu, \nu_\tau)$ the neutral fermion mass matrix $M_N$ is given by

$$M_N = \begin{bmatrix} \mathcal{M}_{\lambda^0}^T & m^T \\ m & 0 \end{bmatrix}$$  \hfill (23)

where $\mathcal{M}_{\lambda^0}$ is the standard MSSM neutralino mass matrix and

$$m = \begin{bmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 \end{bmatrix}$$  \hfill (24)
characterizes the breaking of R-parity.

The mass matrix $M_N$ is diagonalized by

$$N^t M_N N^{-1} = \text{diag}(m_{\chi^0_i}, m_{\nu_j}),$$

(25)

where $(i = 1, \cdots, 4)$ for the neutralinos, and $(j = 1, \cdots, 3)$ for the neutrinos. One of the neutrino species acquire a tree level non–zero mass, given by:

$$m_{\nu_3} = Tr(m_{\text{eff}}) = \frac{M_1 g^2 + M_2 g'^2}{4 \det(M_{\chi^0})} |\vec{\Lambda}|^2,$$

(26)

where $|\vec{\Lambda}|^2 \equiv \sum_{i=1}^{3} \Lambda_i^2$. The $\Lambda_i$ parameters are defined as:

$$\Lambda_i \equiv \mu \nu_i + v_d \epsilon_i$$

(27)

The two other neutrinos can get masses at one–loop as it is discussed in Ref. [18]. For our purposes it will be important to have an estimate of the values of $\Delta m_{12}^2 = m_{\nu_2}^2 - m_{\nu_1}^2$. We will use the results of Ref. [20] where it was found that, to a very good approximation, $m_{\nu_1} = 0$ and

$$m_{\nu_2} = \frac{3}{16 \pi^2} m_b \sin^2 \theta_b \frac{h_b^2}{\mu^2} \log \frac{m_{\tilde{t}_R}^2}{m_{\tilde{t}_L}^2} \left(\epsilon \times \vec{\Lambda}\right)^2$$

(28)

The one–loop contributions to $A_{L,R}$ in eq. 2 arise from the diagrams of Fig. 4. We follow the notation of [7, 18] indicating by $S^\pm$ the eigenstates of the charged scalar mass matrix, by $S^0$ and $P^0$ the eigenstates for the sneutrino–Higgs scalar mass matrices, CP–even and CP–odd, respectively.

For the example considered in Fig. 5 we take, $\tan \beta = 30$, $m_{1/2} = 400$ GeV, $m_0 = 300$ GeV, $A_0 = 0$, in order to compare our results with the ones presented in the previous section. We take a $m_{\nu_3} = 0.1$ eV, which leads to values of the $|\vec{\Lambda}|$ in the
The range of $0.1 - 1 \text{ GeV}^2$, for the values of the SUSY parameters that we will consider. Considering that we take positive values for $\mu$ we should also take negative values for the product $\epsilon_i v_i$ to avoid our analysis to be constrained to small values of $\epsilon_i$.

The six free BRpV breaking parameters $\epsilon_i, v_i$ reduce to three if we take into account the constraints imposed by the predictions for neutrino oscillations in this model, as given in Ref. [18]. It was shown in this reference that the conditions $\Lambda_3 \simeq \Lambda_2 \simeq 5 \times \Lambda_1$ satisfy both the atmospheric neutrino anomaly mixings and the CHOOZ result [2]. We then obtain a linear relationship between each couple $\epsilon_i, v_i$.

We can compare the results presented in Fig. 5 with predictions for $BR(\mu \to e\gamma)$ presented in the previous section. As we can see in Fig. 3, the choice of MSSM parameters used in Fig. 5 corresponds to a value between $10^{-12}$ and $10^{-13}$ for $BR(\mu \to e\gamma)$. These values will be reached in the BRpV case for values of $|\epsilon_1|$ and $|\epsilon_2|$ ranging from 1 to 10 GeV (independently of the value of $\epsilon_3$). Values in the range of 0.1 to 1 GeV would lead to rates of order $10^{-14} - 10^{-16}$, still interesting for the next generation experiments [21, 22]. Such values of $|\epsilon_i|$ are however excluded if one takes into account the constraint coming from the solar neutrinos mass scale. This is shown in Fig. 5, where the dashed line gives the upper limit on the $|\epsilon_i|$ as obtained from Eq. (28) for the requirement that $m_{\nu_2} < 0.01 \text{ eV}$. As it is discussed in Ref. [7], the parameters which enhances the ratios also make $m_{\nu_2}$ larger. From eq.(28) we can observe that $m_{\nu_2}$ increases with $\tan \beta$ (through the dependence on $h_b$) and decreases as the $\mu$-term increases (i.e with $m_{1/2}$ and $m_0$).

Contributions to $\delta a_\mu$ arising from the BRpV terms are found to be small compared with the MSSM limit. The corresponding values for the partial contributions from the diagrams of Fig. 4 can be found in Ref. [7]. Also the prediction of the model for $\tau \to \mu \gamma$ rates is of the same order of the $BR(\mu \to e\gamma)$ presented here, therefore out of the experimental range.

6 Conclusions

We had reviewed the predictions for the rare lepton decays $BR(\mu \to e\gamma)$ and $BR(\tau \to \mu \gamma)$ in the context of SUSY models. The first scenario was used to explain how the nature of the soft–terms combined with a non–trivial texture for the charged lepton Yukawa couplings turns into a prediction for charged lepton flavor violation. In the second scenario, these conditions are obtained when neutrino flavor oscillations are explained trough a “see-saw” mechanism. The predicted rates in both scenarios are of experimental interest and will be tested at PSI [21] or at PRISM [22] providing a relevant information on the free parameters of the models.

The obtained results for the $\mu \to e\gamma$ in our third scenario show us that if the BRpV model is the explanation for both the solar and atmospheric neutrino oscillations, the predicted LFV will not be testable in planned experiments. The correlations of the BRpV parameters with the neutralino decays, as proposed in Ref. [23], will remain the main test of the model.

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