Lepton Flavor Violation at the LHC

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Abstract. In supersymmetric scenarios, the seesaw mechanism involving heavy right-handed neutrinos implies sizable lepton flavor violation (LFV) in the slepton sector. We discuss the potential of detecting LFV processes at the LHC in mSUGRA+seesaw scenarios and for general mixing in either the left- or right-handed slepton sector. The results are compared with the sensitivity of rare LFV $\mu \rightarrow e\gamma$ decay experiments.

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1 SUSY Seesaw Type I and Slepion Mass Matrix

The observed neutrino oscillations imply the existence of neutrino masses and flavor mixing, giving a hint towards physics beyond the Standard Model. For example, the seesaw mechanism involving heavy right handed Majorana neutrinos, which explains well the smallness of the neutrino masses, allows for leptogenesis and induces sizeable lepton flavor violation (LFV) in a supersymmetric extension of the Standard Model.

If three right handed neutrino singlet fields $\nu_R$ are added to the MSSM particle content, one gets additional terms in the superpotential $^{[1]}$:

$$W_\nu = -\frac{1}{2} v^T R M^2 M^T v_R + \nu^T Y_\nu L \cdot H_2. \quad (1)$$

Here, $Y_\nu$ is the matrix of neutrino Yukawas, $M$ is the right handed neutrino Majorana mass matrix, and $L$ and $H_2$ denote the left handed lepton and hypercharge $+1/2$ Higgs doublets, respectively. If the mass scale $M_R$ of the matrix $M$ is much greater than the electroweak scale, and consequently much greater than the scale of the Dirac mass matrix $m_D = Y_\nu \langle H_2^0 \rangle$ (where $\langle H_2^0 \rangle = v \sin \beta$ is the appropriate Higgs v.e.v., with $v = 174$ GeV and $\tan \beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$), the effective left handed neutrino mass matrix $M_\nu$ will be naturally obtained,

$$M_\nu = m_D^T M^{-1} m_D = Y_\nu^T M^{-1} Y_\nu (v \sin \beta)^2. \quad (2)$$

The matrix $M_\nu$ is diagonalized by the unitary matrix $U_{MNS}$, yielding the three light neutrino masses:

$$U_{MNS}^T M_\nu U_{MNS} = \text{diag}(m_1, m_2, m_3). \quad (3)$$

The other three neutrino mass eigenstates are too heavy to be observed directly, but, through virtual corrections, induce small off-diagonal terms in the evolved MSSM slepton mass matrix,

$$m_i^2 = \left( \begin{array}{ll} m^2_{\nu_R} & (m^2_{\nu_R})^T \\ m^2_{\nu_R} & m^2_{\nu_R} \end{array} \right) + \frac{\delta m^2_{\nu_R} \delta m^2_{\nu_R}}{\sin \beta^2}, \quad (4)$$

leading to observable LFV processes. These corrections in leading log approximation are $^{[2]}$

$$\delta m^2_{\nu_R} = -\frac{1}{8\pi^2} (3m^2_0 + A^0_0) Y_{\nu}^T L Y_{\nu}, \quad (5)$$

$$\delta m^2_{L_R} = -\frac{3A_0 \cos \beta}{16\pi^2} (Y_{\nu}^T L Y_{\nu}), \quad (6)$$

where $L_{ij} = \ln(M_{GUT}/M_i) \delta_{ij}$, and $m_0$ and $A_0$ are the common scalar mass and trilinear coupling, respectively, of the minimal supergravity (mSUGRA) scheme. The product of the neutrino Yukawa couplings $Y_{\nu}^T L Y_{\nu}$ entering these corrections can be determined by inverting $^{[2]}$.

$$Y_{\nu} = \frac{1}{v \sin \beta} \text{diag}(\sqrt{M_1}) \cdot R \cdot \text{diag}(\sqrt{m_i}) \cdot U_{MNS}^T, \quad (7)$$

using neutrino data as input for the masses $m_i$ and $U_{MNS}$, and evolving the result to the unification scale $M_{GUT}$. The unknown complex orthogonal matrix $R$ may be parametrized in terms of 3 complex angles $\theta_i = x_i + iy_i$.

2 LFV Rare Decays and LHC Processes

At the LHC, a feasible test of LFV is provided by production of squarks and gluinos, followed by cascade decays via neutralinos and sleptons $^{[34]}$.

$pp \rightarrow q_0 q_3, \tilde{g} q_0, \tilde{g} q_0, \tilde{g} q_0.$
\[
\tilde{q}_a(g) \rightarrow \tilde{\chi}_2^0 q_a(g), \\
\tilde{\chi}_2^0 \rightarrow \tilde{l}_a l_i, \\
\tilde{l}_a \rightarrow \tilde{\chi}_1^0 l_j, 
\]

where \(a, b, i\) run over all particle mass eigenstates including antiparticles. LFV can occur in the decay of the second lightest neutralino and/or the slepton, resulting in different lepton flavors, \(\alpha \neq \beta\). The total cross section for the signature \(l_\alpha^+ l_\beta^- + X\) can then be written as

\[
\sigma(pp \rightarrow l_\alpha^+ l_\beta^- + X) = \\
\left\{ \sum_{a,b} \sigma(pp \rightarrow \tilde{q}_a \tilde{q}_b) \times Br(\tilde{q}_a \rightarrow \tilde{\chi}_2^0 q_a) \\
+ \sum_a \sigma(pp \rightarrow \tilde{q}_a g) \times Br(\tilde{q}_a \rightarrow \tilde{\chi}_2^0 g) \\
+ \sigma(pp \rightarrow g g) \times Br(g \rightarrow \tilde{\chi}_2^0 g) \right\} \times Br(\tilde{\chi}_2^0 \rightarrow l_\alpha^+ l_\beta^- \tilde{\chi}_1^0), 
\]

where \(X\) can involve jets, leptons and LSPs produced by lepton flavor conserving decays of squarks and gluinos, as well as low energy proton remnants. The cross section is calculated at the LO level with 5 active quark flavors, using CTEQ6M PDFs. Possible signatures of this inclusive process are:

- \(l_i l_j + 2\text{jets} + E_{\text{miss}}\)
- \(l_i l_j + 3\text{jets} + E_{\text{miss}}\)
- \(l_i l_j \ell_k \ell_k + 2\text{jets} + E_{\text{miss}}\),

with at least two leptons \(l_i, l_j\) of unequal flavor.

The LFV branching ratio \(Br(\tilde{\chi}_2^0 \rightarrow l_\alpha^+ l_\beta^- \tilde{\chi}_1^0)\) is for example calculated in [7] in the framework of model-independent MSSM slepton mixing. In general, it involves a coherent summation over all intermediate slepton states.

As a sensitivity comparison it is useful to correlate the expected LFV event rates at the LHC with LFV rare decays (see [8] and references therein for a discussion of LFV rare decays in SUSY Seesaw Type I scenarios). This is shown in Figures 1 and 2 for the event rates \(N(\tilde{\chi}_2^0 \rightarrow \mu^+ e^- \tilde{\chi}_1^0)\) and \(N(\tilde{\chi}_2^0 \rightarrow \tau^+ \mu^- \tilde{\chi}_1^0)\), respectively, originating from the cascade reactions (8).

Both are correlated with \(Br(\mu \rightarrow e\gamma)\), yielding maximum rates of around \(10^{-3}\) per year for an integrated luminosity of \(100\,\text{fb}^{-1}\) in the mSUGRA scenario C [9], consistent with the current limit \(Br(\mu \rightarrow e\gamma) < 10^{-11}\). The MEG experiment at PSI is expected to reach a sensitivity of \(Br(\mu \rightarrow e\gamma) \approx 10^{-13}\).

The correlation is approximately independent of the neutrino parameters, but highly dependent on the mSUGRA parameters. This is contemplated further in Figure 3 comparing the sensitivity of the signature \(N(\tilde{\chi}_2^0 \rightarrow \mu^+ e^- \tilde{\chi}_1^0)\) at the LHC with \(Br(\mu \rightarrow e\gamma)\) in the mSUGRA \(m_0 - m_{1/2}\) parameter plane. LHC searches can be competitive to the rare decay experiments for small \(m_0 \approx 200\,\text{GeV}\). Tests in the large-\(m_0\) region are severely limited by collider kinematics.

Up to now we have considered LFV in the class of type I SUSY seesaw model described in Section 1 which is representative of models of flavor mixing in the left-handed slepton sector only. However, it is instructive to analyze general mixing in the left- and right-handed slepton sector, independent of any underlying model for slepton flavor violation. The easiest way to achieve this is by assuming mixing between two flavors only, which can be parametrized by a mixing angle \(\theta_{L/R}\) and a mass difference \((\Delta m)_{L/R}\) between the sleptons, in the case of left-/right-handed slepton mixing, respectively [10]. In particular, the left- /right-handed selectron and smuon sector is then di-
Maximal LFV is thus achieved by choosing \( \theta \) diagonalized by

$$
\begin{bmatrix}
\hat{t}_1 \\
\hat{t}_2
\end{bmatrix} = U \cdot \begin{bmatrix}
\hat{e}_{L/R} \\
\hat{\mu}_{L/R}
\end{bmatrix}
$$

(10)

with

$$
U = \begin{pmatrix}
\cos \theta_{L/R} & \sin \theta_{L/R} \\
-\sin \theta_{L/R} & \cos \theta_{L/R}
\end{pmatrix},
$$

and a mass difference \( m_{\hat{t}_2} - m_{\hat{t}_1} = (\Delta m)_{L/R} \) between the slepton mass eigenvalues. The LFV branching ratio \( Br(\hat{\chi}_2^0 \rightarrow \mu^+ e^- \hat{\chi}_1^0) \) can then be written in terms of the mixing parameters and the flavor conserving branching ratio \( Br(\hat{\chi}_2^0 \rightarrow e^+ e^- \hat{\chi}_1^0) \) as

$$
Br(\hat{\chi}_2^0 \rightarrow \mu^+ e^- \hat{\chi}_1^0) = 2 \sin^2 \theta_{L/R} \cos^2 \theta_{L/R}
\times \frac{(\Delta m)^2_{L/R}}{(\Delta m)^2_{L/R} + I_r^2}
\times Br(\hat{\chi}_2^0 \rightarrow e^+ e^- \hat{\chi}_1^0),
$$

(12)

with the average width \( I_r \) of the two sleptons involved. Maximal LFV is thus achieved by choosing \( \theta_{L/R} = \pi/4 \) and \((\Delta m)_{L/R} \gg I_r \). For definiteness, we use \((\Delta m)_{L/R} = 0.5 \text{ GeV}\). The results of this calculation can be seen in Figures 4 and 5 which show contour plots of \( N(\hat{\chi}_2^0 \rightarrow \mu^+ e^- \hat{\chi}_1^0) \) in the \( m_0 - m_{1/2} \) plane for maximal left- and right-handed slepton mixing, respectively. Also displayed are the corresponding contours of \( Br(\mu \rightarrow e \gamma) \). We see that the present bound \( Br(\mu \rightarrow e \gamma) = 10^{-11} \) still permits sizeable LFV signal rates at the LHC. However, \( Br(\mu \rightarrow e \gamma) < 10^{-13} \) would largely exclude the observation of such an LFV signal at the LHC.

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