# Large lepton flavour violating signals in supersymmetric particle decays

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**Abstract**

We study lepton flavour violating signals at a future $e^+e^-$ linear collider within the general MSSM, allowing for the most general flavour structure. We demonstrate that there is a large region in parameter space with large signals, while being consistent with present experimental bounds on rare lepton decays such as $\mu^- \to e^-\gamma$. In our analysis, we include all possible signals from charged slepton, sneutrino, neutralino, and chargino production and decay. We also consider the background from the Standard Model *and* the MSSM. We find that in general the signature $e\tau \not{E}_T$ is the most pronounced one.

## 1 Introduction

Neutrino experiments have established the existence of lepton flavour violation (LFV). On the one side, the results of Super-Kamiokande yield an almost maximal mixing between $\nu_\mu$ and $\nu_\tau$ [1] and also the latest results of SNO [2] suggest that also the $\nu_e - \nu_\mu$ sector contains a large mixing, whereas the third mixing between $\nu_e$ and $\nu_\tau$ has to be small [3]. On the other side, there are stringent constraints on LFV in the charged lepton sector, the strongest being $BR(\mu^- \to e^-\gamma) < 1.2 \times 10^{-11}$ [4]. Others are $BR(\mu^- \to e^-e^+e^-) < 10^{-12}$, $BR(\tau^- \to e^-\gamma) < 2.7 \times 10^{-6}$, $BR(\tau^- \to \mu^-\gamma) < 1.1 \times 10^{-6}$. The Standard Model can account for the lepton flavour conservation in the charged lepton sector, but has to be extended to account for neutrino masses and mixings, e.g. by the see-saw mechanism and by introducing heavy right-handed Majorana neutrinos [5].

In general, a gauge and supersymmetric invariant theory does neither conserve total lepton number $L = L_e + L_\mu + L_\tau$ nor individual lepton number $L_e$, $L_\mu$ or $L_\tau$. One usually invokes R-parity symmetry, which forces total lepton number conservation but still allows the violation of individual lepton number, e.g. due to loop effects in $\mu^- \to e^-\gamma$ [6]. The Minimal Supersymmetric Standard Model (MSSM) with R-parity conservation embedded in a GUT theory induces LFV [7] at the weak scale. This is a consequence of having leptons and quarks in the same GUT multiplet and of the quark flavour mixing due to the CKM matrix. A general analysis of flavour changing neutral (FCNC) effects in K- and B-meson as well as in lepton physics was recently performed in [8].

Moreover, in the MSSM a large $\nu_\mu$-$\nu_\tau$ mixing can lead to a large $\tilde{\nu}_\mu$-$\tilde{\nu}_\tau$ mixing via renormalisation group equations [9]. This leads to clear LFV signals in slepton and sneutrino production and in the decays of neutralinos and charginos into sleptons and sneutrinos at the LHC [10] and at future lepton colliders [11]. Signatures due to $\tilde{e}_R$-$\tilde{\mu}_R$ mixing were discussed in [12]. In all these studies, it has been assumed that only one lepton flavour violating term dominates.

In this contribution, we present the results of [13] where we have studied the consequences of LFV in the sfermion sector at future $e^+e^-$ colliders, and we give additional new results. Assuming the *most general* mass matrices for sleptons and sneutrinos, we demonstrate that large signals are expected while at the same time respecting present bounds on rare lepton decays.

# 2 Lepton Flavour Violation in the MSSM

The most general charged slepton $6 \times 6$ mass matrix including left-right mixing as well as flavour mixing is given by:

$$M_{\tilde{l}}^2 = \begin{pmatrix} M_{L,ij}^2 + \frac{1}{2} v_d^2 Y_{ki}^{E*} Y_{kj}^E + D_L \delta_{ij} & \frac{1}{\sqrt{2}}(v_d A_{ji} - \mu^* v_u Y_{ij}^{E*}) \\ \frac{1}{\sqrt{2}}(v_d A_{ji}^* - \mu v_u Y_{ij}^E) & M_{R,ij}^2 + \frac{1}{2} v_d^2 Y_{ik}^E Y_{jk}^{E*} - D_R \delta_{ij} \end{pmatrix} \quad (1)$$

with $D_L = \frac{1}{8}\left(g'^2 - g^2\right)(v_d^2 - v_u^2)$ and $D_R = \frac{1}{4} g'^2 (v_d^2 - v_u^2)$. The indices $i, j, k = 1, 2, 3$ characterize the flavors $e, \mu, \tau$. $M_{LL}^2$ and $M_{RR}^2$ are the soft SUSY breaking mass matrices for left and right sleptons, respectively. $A_{ij}$ are the trilinear soft SUSY breaking couplings of the sleptons and Higgs bosons. The physical mass eigenstates states $\tilde{l}_n$ are given by $\tilde{l}_n = R_{nm}^{\tilde{l}} \tilde{l}'_m$ with $l'_m = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)$. Similarly, one finds for the sneutrinos

$$M_{\tilde{\nu},ij}^2 = M_{L,ij}^2 + \frac{1}{8}\left(g^2 + g'^2\right)(v_d^2 - v_u^2)\delta_{ij} \quad (2)$$

with the physical mass eigenstates $\tilde{\nu}_i = R_{ij}^{\tilde{\nu}} \tilde{\nu}'_j$ and $\tilde{\nu}'_j = (\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)$. The relevant interactions for this study are given by:

$$\mathcal{L} = \bar{l}_i (c_{ikm}^L P_L + c_{ikm}^R P_R) \tilde{\chi}_k^0 \tilde{l}_m + \bar{l}_i (d_{ilr}^L P_L + d_{ijr}^R P_R) \tilde{\chi}_l^- \tilde{\nu}_r + \bar{\nu}_i (e_{ilm}^R P_R) \tilde{\chi}_l^+ \tilde{l}_m + h.c. \quad (3)$$

with

$$c_{ikm}^L = -\sqrt{2} g' (R_{m,i+3}^{\tilde{l}})^* N_{k1}^* - (R_{mi}^{\tilde{l}})^* Y_{ii}^E N_{k3}^* \quad (4)$$

$$c_{ikm}^R = (R_{ki}^{\tilde{l}})^* \frac{g' N_{k1} + g N_{k2}}{\sqrt{2}} - (R_{m,i+3}^{\tilde{l}})^* Y_{ii}^E N_{j3} \quad (5)$$

$$d_{ilr}^L = Y_{ii}^E (R_{ri}^{\tilde{\nu}})^* U_{l2}^*, \qquad d_{ilr}^R = -g * (R_{ri}^{\tilde{\nu}})^* V_{l1} \quad (6)$$

$$e_{ilm}^R = \sum_r \left( -g (R_{mr}^{\tilde{l}})^* R_{ir}^{\nu} U_{l1} + Y_{rr}^E (R_{m,r+3}^{\tilde{l}})^* R_{ir}^{\nu} U_{l2}^* \right) \quad (7)$$

where we have chosen the basis where the charged lepton Yukawa coupling is diagonal $Y_{ij}^E = \sqrt{2} m_i / v_d \delta_{ij}$. $R_{ij}^{\nu}$ is the neutrino mixing matrix, $N$ diagonalises the neutralino mass matrix in the basis $\tilde{B}, \tilde{W}_3, \tilde{H}_u^0, \tilde{H}_d^0$ and $U$ and $V$ are the mixing matrices of the charginos. The first two terms in Eq. (3) give rise to LFV signals whereas the last one will give rise to the SUSY background.

As mentioned above, most studies so far consider the case where only one of the flavour mixing entries in Eqs. (1) and/or (2) is non-zero. It is the purpose of this study to allow for all possible flavour violating entries in Eqs. (1) and (2) which are compatible with the present bounds on lepton number violating processes, such as $\mu^- \to$

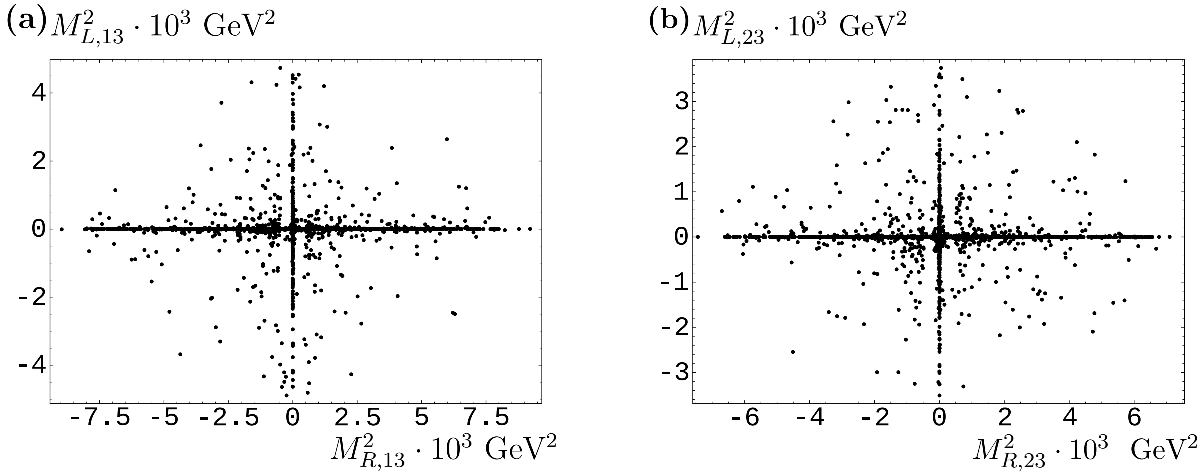


Figure 1: Ranges for parameters inducing lepton number violation.

$e^-\gamma, e^-e^+e^-$, $\tau^- \to e^-\gamma$, $\tau^- \to \mu^-\gamma$ and $Z \to e\mu, e\tau, \mu\tau$. For definiteness, we have taken the first of the mSUGRA points of Snowmass' 01 [14]: $M_{1/2} = 250$ GeV, $M_0 = 100$ GeV, $A'_0 = -100$ GeV, $\tan\beta = 10$ and sign$(\mu) = +$. Note that $A'_0$ has to be multiplied by the Yukawa couplings to get the $A_{ij}$ parameters of Eq. (1). This leads to the following slepton mass parameters at the electroweak scale: $M_{R_{11}} = 138.7$ GeV, $M_{R_{33}} = 136.3$ GeV, $M_{L_{11}} = 202.3$ GeV, $M_{L_{33}} = 201.5$ GeV and $A_{33}/Y^E_{33} =$ -257.3 GeV. Some typical masses are: $m_{\tilde{e}_R} = 146.9$ GeV, $m_{\tilde{e}_L} = 214.7$ GeV, $m_{\tilde{\nu}_e} = 199.4$ GeV, $m_{\tilde{\tau}_1} = 138.6$ GeV, $m_{\tilde{\tau}_2} = 217.7$ GeV, $m_{\tilde{\chi}^+_1} = 193.6$ GeV, $m_{\tilde{\chi}^0_1} = 103.1$ GeV, $m_{\tilde{\chi}^0_2} = 194.6$ GeV, $m_{A^0} = 395$ GeV and $m_{\tilde{t}_1} = 407$ GeV (the remaining masses are given in [13]). We keep all parameters fixed except for the slepton parameters $M^2_L$, $M^2_R$ and $A$ where all entries are varied in the whole range compatible with the experimental constraints.

We find values for $|M^2_{R,ij}|$ up to $8 \cdot 10^3$ GeV$^2$, $|M^2_{L,ij}|$ up to $6 \cdot 10^3$ GeV$^2$ and $|A_{ij} v_d|$ up to 650 GeV$^2$ compatible with the constraints. In most cases, one of the mass squared parameters is at least one order of magnitude larger than all the others. However, there is a sizable part in parameters where at least two of the off-diagonal parameters have the same order of magnitude as shown in Fig. 1.

# 3 Signals

In what follows, we concentrate on possible LFV signals at a 500 GeV $e^+e^-$ collider: $e\mu \not{E}_T$, $e\tau \not{E}_T$, $\mu\tau \not{E}_T$, as well as the possibility of additional jets. We have generated 8000 points consistent with the experimental data, varying the parameters randomly on a logarithmic scale: $10^{-8} \leq |A_{ij}| \leq 50$ GeV, $10^{-8} \leq M^2_{ij} \leq 10^4$ GeV$^2$. We consider the following SUSY processes: $e^+e^- \to \tilde{l}^-_i \tilde{l}^+_j, \tilde{\nu}_{i'} \bar{\tilde{\nu}}_{j'}, \tilde{\chi}^0_k \tilde{\chi}^0_m, \tilde{\chi}^+_n \tilde{\chi}^-_o$ as well as stop and Higgs production. We take into account all possible SUSY and Higgs cascade decays. We have taken into account ISR- and SUSY-QCD corrections for the production cross sections.

The main sources for the LFV signal stem from production of sleptons, sneutrinos and their decays, for example:

$$e^+e^- \to \tilde{l}^-_i \tilde{l}^+_j \to l^-_k l^+_m 2\tilde{\chi}^0_1 \,. \tag{8}$$

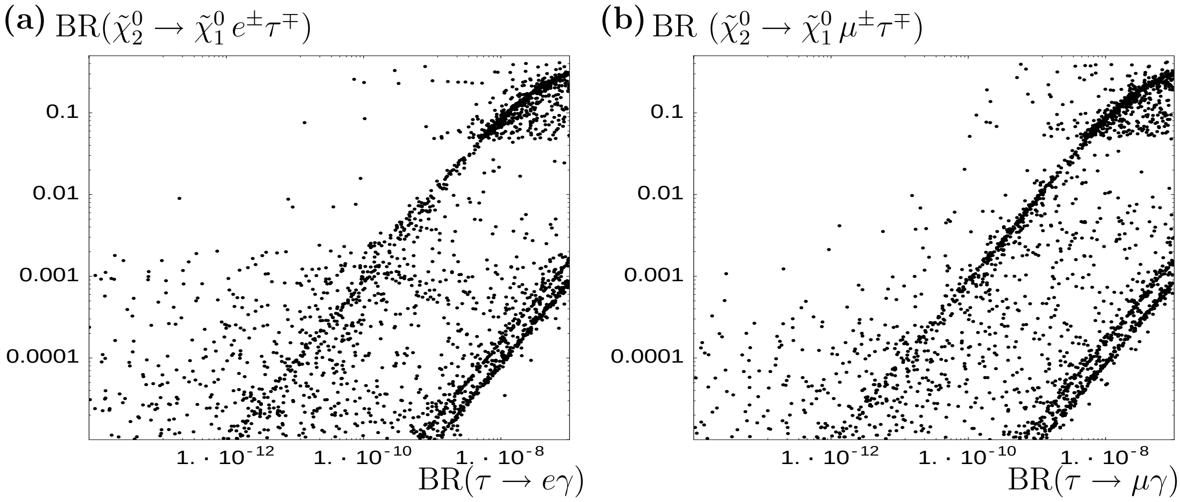


Figure 2: Flavour violating decays of the second lightest neutralino.

Moreover, also the decays of the second lightest neutralino give an important contribution as shown in Fig. 2. There are two main reasons for the large flavour violating branching ratios of $\tilde{\chi}_2^0$ in some parts of the parameter space: (i) There is no negative interference terms with a $Z$–boson exchange as in the case of flavour conserving decays into leptons. (ii) The squarks are substantially heavier than the sleptons in this scenario. The cross section for the LFV signal $e\tau \not{E}_T$ can go up to 250 fb if both beams are polarized leading to about $10^4$ events with a luminosity of 100 fb$^{-1}$. In the case of two leptons with different flavors and 2 jets we find cross sections up to 1.5 fb [13], we have put a veto on b-jets because of the large background stemming from $t$-quark production.

For the background we take into account all possible SUSY cascade decays faking the signal and the Standard Model background from $W$-boson pair production, $t$-quark pair production and $\tau$-lepton pair production. The SM background has been calculated with the program Whizard [15]. A SUSY background reaction is, for example, the chain $\tilde{\chi}_r^0 \to l_j^- \nu_i \tilde{\chi}_s^+ \to l_j^- \nu_i l_k^+ \nu_n \tilde{\chi}_m^0$. In Fig. 3 we show the cross section of $e^+e^- \to e^\pm \tau^\mp \not{E}_T$ and the corresponding ratio signal over square root of the background ($S/\sqrt{B}$) as a function $BR(\tau^- \to e^-\gamma)$ assuming an integrated luminosity of 100 fb$^{-1}$. Although no cuts have been applied, there is in most cases a spectacular signal. The cases where the ratio $S/\sqrt{B}$ is of order 1 or smaller should clearly improve, once appropriate cuts are applied. For example, a cut on the angular distribution of the final state leptons will strongly reduce the $WW$ background. Further cuts as applied in the study of slepton production [16] will enhance the ratio $S/\sqrt{B}$. The accumulation of points in Fig. 3 along a band is due to a large $\tilde{e}_R$-$\tilde{\tau}_R$ mixing which is less constraint by $\tau^- \to e^-\gamma$ than the corresponding left-left or left-right mixing.

Let us shortly comment on the situation where neutrino data are not explained by the see–saw mechanism but due to bilinear terms in the superpotential breaking R-parity (see e.g. [17] and references therein). It has been shown that the additional R–parity breaking contributions to processes such as $\mu^- \to e^-\gamma$ are negligible [18] so that the same ranges of flavour violating parameters as in the study above are allowed. Thus the same sources for the various signals plus additional leptons stemming from the LSP decays

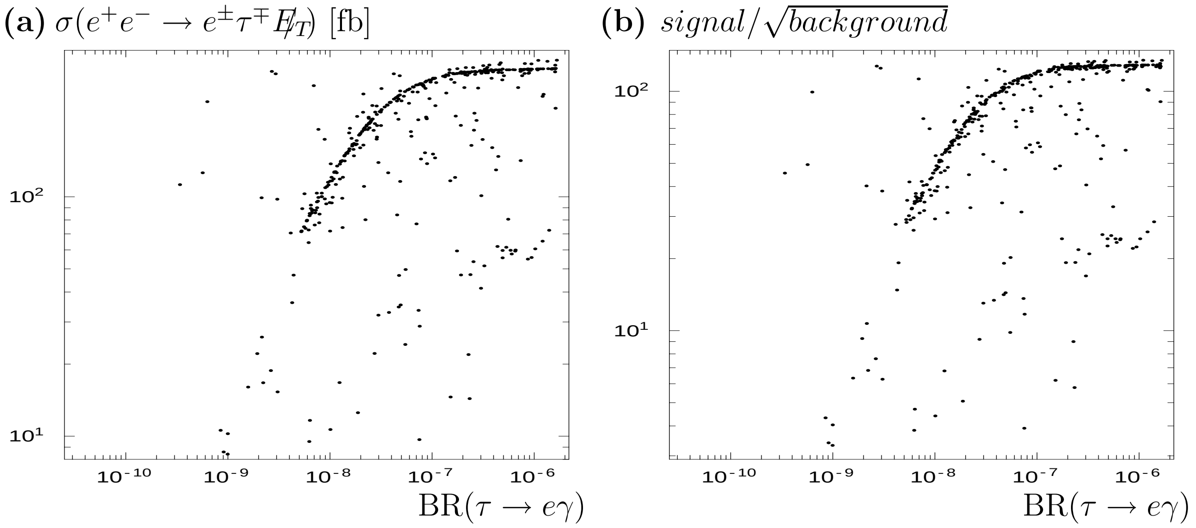


Figure 3: (**a**) Cross section in fb for the signal $e^\pm\tau^\mp \not{E}_T$ and (**b**) the ratio signal over square root of background as a function of BR($\tau \to e\gamma$) for $\sqrt{s} = 500$ GeV, $P_{e^-} = 0$ and $P_{e^+} = 0$. In the latter case we have assumed an integrated luminosity of 100 fb$^{-1}$.

(see e.g. [19]) are present. This clearly will lead to even larger signals, in particular those containing additional jets.

# 4 Summary

In conclusion, we have shown that the most general flavour violating structure of the slepton and sneutrino mass matrix may lead to large lepton flavour violating signals at a future $e^+e^-$ collider – despite the strong constraints on rare lepton decays.

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