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SLEPTON FLAVOUR VIOLATION AT COLLIDERS

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Dedicated to Stefan Pokorski on his 60th birthday

In supersymmetric extensions of the Standard Model (SM), the Lepton Flavour Violation (LFV) is closely related to the structure of slepton masses and mixing. Allowing for the most general flavour structure of the slepton sector, consistent with the experimental limits on rare lepton decays, large and distinct signals of LFV at future colliders can be expected. A case study of mixing of second and third generation of sleptons at an e^+e^- collider is presented and compared to that of $\tau \to \mu\gamma$ rare decay.

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Observations of flavour changing neutral current processes provide important tests of physics beyond the Standard Model. It is well known that in the Standard Model the renormalizability, Lorentz and gauge invariance force the individual lepton flavour numbers L_e, L_μ and L_τ to be conserved in addition to the conserved baryon B and total lepton L numbers. These conservation laws are consequences of global symmetries which are "accidental" in the sense that they follow from the spin and gauge quantum number assignments of the SM fields.

Experiments on solar and atmospheric neutrinos [1] provide a compelling evidence for oscillations among three active neutrinos with different masses. This phenomenon is lepton flavour violating and it is a first direct evidence for physics beyond the Standard Model. The most favoured model to account for the neutrino masses and their oscillations is the seesaw mechanism [2] with heavy right-handed neutrinos N. The smallness of m_{ν_i} is obtained in a natural way if the masses of right-handed neutrinos are assumed in the range $M_N \sim 10^{13}$–10^{15} GeV, and non-diagonal elements of the Yukawa couplings of N and ν generate neutrino mixing. Radiative corrections due to these couplings also induce flavour mixing in the charged lepton sector.

An interesting question then arises whether processes with charged-lepton flavour violation, like $\mu \to e\gamma$, $\tau \to \mu\gamma$ *etc.*, can be generated at observable rates [3].

In the Standard Model with right-handed neutrinos the charged LFV decays are strongly suppressed [4] via the GIM mechanism ($\sim \Delta m_\nu^4/M_W^4$). In the supersymmetric extension of this model, however, the situation of LFV processes may be quite different. In addition to the seesaw mechanism, new sources of flavour violation in the leptonic sector can be generated by soft supersymmetry breaking terms, *e.g.*

$$\mathcal{L}_{\rm soft} \ni m^2_{{\rm L}\alpha\beta}\, \tilde{e}^*_\alpha \tilde{e}_\beta + m^2_{{\rm R}\alpha\beta} \tilde{e}^*_\alpha \tilde{e}_\beta + (A_{\alpha\beta}\, \tilde{e}^*_\alpha h^0_1 \tilde{e}_\beta + {\rm h.c.})\,, \tag{1}$$

where only scalar mass and trilinear terms in the leptonic sector have been written explicitly using self-explanatory notation, $\alpha, \beta = e, \mu, \tau$. The trilinear term, after electroweak symmetry breaking, couples left- and right-handed charged sleptons through the mass matrix $m^2_{{\rm LR}\alpha\beta}$ which receives a contribution from $A_{\alpha\beta}\langle h^0_1\rangle$. In general the slepton mass matrix need not simultaneously be diagonalised with leptons. If we now rotate sleptons to the mass eigenstate basis, $\tilde{e}_i = W_{i\alpha}\, \tilde{e}_\alpha$, the slepton-mass diagonalisation matrix $W_{i\alpha}$ enters the chargino and neutralino couplings

$$\tilde{e}_i {W^*}_{i\alpha} \bar{e}_\alpha \tilde{\chi}^0 + \tilde{\nu}_i {W^*}_{i\alpha} \bar{e}_\alpha \tilde{\chi}^- + \ldots \tag{2}$$

and mixes lepton flavour (Latin and Greek subscripts are slepton mass-eigenstate and flavour indices, respectively). Contributions form virtual slepton exchanges can, therefore, enhance the rates of rare decays, like $\mu \to e\gamma$. Although these contributions are suppressed through the superGIM mechanism by $\Delta m_{\tilde{l}}/\bar{m}_{\tilde{l}}$ with the mass difference $\Delta m_{\tilde{l}}$ and the average mass $\bar{m}_{\tilde{l}}$ of the sleptons, the present experimental upper limits on these processes [5] impose already strong bounds on LFV sources in the slepton sector, in particular for the first two generations of sleptons.

Even if the slepton mass matrix is assumed to be flavour conserving at tree level to avoid the supersymmetric flavour-changing problem, like in minimal supergravity or gauge mediated SUSY breaking models, the off-diagonal terms can be induced radiatively in the framework of the seesaw mechanism. The reason is that non-diagonal neutrino mass terms originating from the lepton Yukawa coupling contribute to the renormalisation-group running of $m^2_{{\rm L}ij}$, $m^2_{{\rm R}ij}$ and A_{ij} matrices [6], inducing flavour-mixing entries.

In extended models, however, additional off-diagonal entries are in general generated. For example, in models with quarks and leptons unified in larger multiplets the non-diagonal terms are generated radiatively by the top quark Yukawa couplings [7]. Also string-inspired models naturally lead to non-universal soft-SUSY breaking terms [8]. Flavour changing slepton exchanges originating from these additional terms can significantly contribute to neutrino masses and mixings linking, for example, substantial $\nu_\mu - \nu_\tau$ mixing with large $\tilde{\mu}_{\rm L} - \tilde{\tau}_{\rm L}$ and $\tilde{\nu}_\mu - \tilde{\nu}_\tau$ mixings. It is an interesting and open question whether these terms are required to account for the observed pattern of neutrino masses and mixings [9].

Once super-partners are discovered, it will be possible to probe lepton flavour violation directly in their production and decay at future colliders. A flavour-violating signal is obtained from the production of real sleptons (either directly or from chain decays of other sparticles), followed by their subsequent decays into different flavour leptons, with missing energy and jets in the final state. Searches for these signals have a number of advantages. First, once kinematically accessible, super-partners are produced with large cross sections. Second, flavour changing decays of sleptons occur at tree level while rare radiative decays of leptons at one-loop. Third, they are suppressed only as $\Delta m_{\tilde{l}}/\Gamma_{\tilde{l}}$ [10] in contrast to the $\Delta m_{\tilde{l}}/m_{\tilde{l}}$ suppression of radiative decays — an important difference since $m_{\tilde{l}}/\Gamma_{\tilde{l}}$ is typically of the order of 10^2–10^3. As a result, allowing for the most general slepton mass matrix respecting present bounds on rare lepton decays, large LFV signals are expected both at the LHC [11] and e^+e^- colliders [10, 12–15]. All the above features suggest that future e^+e^- colliders (and also the LHC in some favourable cases) may provide a more powerful tool to search for and explore supersymmetric lepton flavour violation than rare decay processes.

In this work we concentrate on the question how well models of LFV can be probed at future e^+e^- colliders. As a case study we consider a pure 2–3 intergeneration mixing between $\tilde{\nu}_\mu$ and $\tilde{\nu}_\tau$, generated by a near-maximal mixing angle θ_{23}, and ignore any mixings with $\tilde{\nu}_e$. Our work is closely related to, and extension of, Ref. [14] by comparing the expected reach at the e^+e^- collider to that from the rare decay process $\tau \to \mu\gamma$.

The scalar neutrino mass matrix $M^2_{\tilde{\nu}}$, restricted to the 2–3 generation subspace, can be written in the flavour basis as

$$M^2_{\tilde{\nu}} = \begin{pmatrix} \cos\theta_{23} & -\sin\theta_{23} \\ \sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} m_{\tilde{\nu}_2} & 0 \\ 0 & m_{\tilde{\nu}_3} \end{pmatrix} \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \qquad (3)$$

where $m_{\tilde{\nu}_2}$ and $m_{\tilde{\nu}_3}$ are the physical masses of $\tilde{\nu}_2$ and $\tilde{\nu}_3$, respectively. Its off-diagonal element is related to physical masses and mixing angle by

$$\left(M^2_{\tilde{\nu}}\right)_{\mu\tau} = \tfrac{1}{2}\left(m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_3}\right)\sin 2\theta_{23}\,. \qquad (4)$$

In the following we take the mixing angle θ_{23} and $\Delta m_{23} = |m_{\tilde{\nu}_2} - m_{\tilde{\nu}_3}|$ as free, independent parameters. The same goes for the charged slepton sector, modulo standard LR mixing, where θ_{23} and Δm_{23} are then the corresponding parameters for charged sleptons.

In discussing supersymmetric LFV collider signals one has to consider two cases in which oscillation of lepton flavour can occur in processes with single (uncorrelated) or correlated slepton pair production. The difference comes from the quantum interference between production and decay [10].

Uncorrelated sleptons may be produced in cascade decays of heavier non-leptonic super-particles. Such processes are particularly important for hadron colliders, where sleptons can be products of uncorrelated decays of gluinos or squarks, but they may also be relevant for lepton colliders where single slepton can be a decay product of a chargino or neutralino. The cross section for the process

$$f\,f' \to e^+_\alpha\,X\,\tilde{e}^-_i \to e^+_\alpha\,X\,e^-_\beta\,Y \tag{5}$$

assuming negligible generation dependence, nearly degenerate in mass and narrow sleptons, Δm^2_{ij}, $m\Gamma \ll m^2$, and the case of 2–3 intergeneration mixing, takes the simple form [16]

$$\begin{aligned} \sigma_{\alpha\beta} &= \chi_{23}\sin^2 2\theta_{23}\;\sigma(f\,f' \to e^+_\alpha\,X\,\tilde{e}^-_\alpha) \\ &\quad \times \mathrm{BR}\left(\tilde{e}^-_\alpha \to e^-_\alpha\,Y\right)\,, \end{aligned} \tag{6}$$

$$\chi_{23} = \frac{x^2_{23}}{2\left(1+x^2_{23}\right)}, \qquad x_{23} = \Delta m_{23}/\Gamma\,. \tag{7}$$

Correlated slepton pair production is the dominant slepton production mechanism at lepton colliders, but it may also occur at hadron colliders when sleptons are produced in the Drell–Yan process. Assuming only the s-channel production mechanism and the same approximations as in the previous case, the cross section for the process

$$\bar{f}\,f \to \tilde{e}^+_i\,\tilde{e}^-_i \to e^+_\alpha\,X\,e^-_\beta\,Y \tag{8}$$

can be written as

$$\begin{aligned} \sigma_{\alpha\beta} &= \chi_{23}(3-4\chi_{23})\sin^2 2\theta_{23}\;\sigma(\bar{f}\,f \to \tilde{e}^+_\alpha\,\tilde{e}^-_\alpha) \\ &\quad \times \mathrm{BR}\left(\tilde{e}^+_\alpha \to e^+_\alpha\,X\right) \times \mathrm{BR}\left(\tilde{e}^-_\alpha \to e^-_\alpha\,Y\right)\,. \end{aligned} \tag{9}$$

In the limit $x_{23} \gg 1$, χ_{23} approaches $1/2$, the interference can be neglected and the cross section behaves as $\sigma \sim \sin^2 2\theta_{23}$. In the opposite case, the interference suppresses the flavour changing process, $\sigma \sim (\Delta m_{23}\sin 2\theta_{23}/\Gamma)^2$. The effect of the factor χ_{23} determines the characteristic features of the contour lines of the constant cross sections in the plane $\Delta m_{23} - \sin 2\theta_{23}$, which are also visible in Fig. 1, where the results of our analysis are shown.

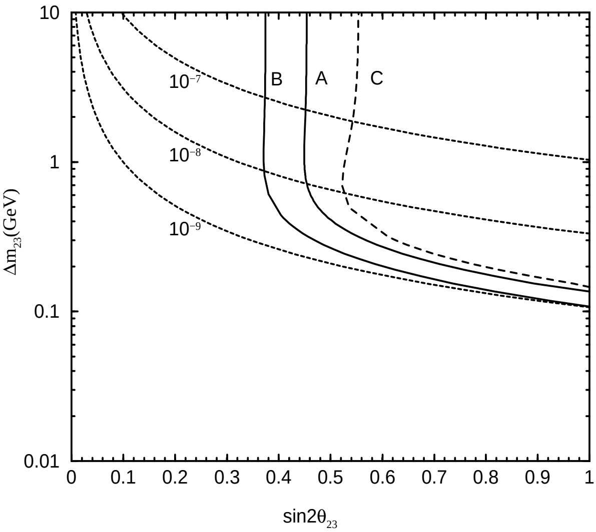

Fig. 1. The 3σ significance contours (for the SUSY point mentioned in the text) in $\Delta m_{23} - \sin 2\theta_{23}$ plane for $\sqrt{s}$ = 500 GeV and for different luminosity options, contours (A) and (B) being for 500 fb^{-1} and 1000 fb^{-1}, respectively. The dashed line is for only $\tilde{\nu}\tilde{\nu}^c$ contribution with luminosity 500 fb^{-1}. The dotted lines show contours for BR($\tau \to \mu\gamma$)=10^{-7}, 10^{-8} and 10^{-9}.

Our analysis for the LFV signal and background at a 500 GeV e^+e^- linear collider has been performed for one of the MSSM representative points chosen for detailed case studies at the ECFA/DESY [17]. This point is given in terms of a mSUGRA scenario defined by: $m_0 = 100$ GeV, $M_{1/2} = 200$ GeV, $A_0 = 0$ GeV, $\tan\beta = 3$ and sgn(μ) = +. The corresponding masses of chargino, neutralino and slepton states, along with some branching ratios, relevant for the LFV processes at $\sqrt{s}$ = 500 GeV are shown in Table I.

TABLE I

The masses (in GeV) and the branching ratios for decay modes of light supersymmetric particles which are relevant to our study. No slepton mixing is assumed. ℓ denotes e or μ, and τ unless the entry for τ is explicitly shown.

	Mass	Decay	BR		Mass	Decay	BR
$\tilde{\chi}_1^+$	128	$\tilde{\chi}_1^0 q\bar{q}'$	0.56	$\tilde{\chi}_1^0$	72		
$\tilde{\chi}_2^+$	346	$\ell^+\tilde{\nu}_\ell$	0.03 × 3	$\tilde{\chi}_2^0$	130	$\tilde{\chi}_1^0\ell^+\ell^-$	0.64
$\tilde{\ell}_{\rm L}^-$	176	$\tilde{\chi}_1^-\nu_\ell$	0.53	$\tilde{\nu}_\ell$	161	$\tilde{\chi}_1^+\ell^-$	0.48
$\tilde{\tau}_1^-$	131	$\tilde{\chi}_1^0\tau^-$	1.00	$\tilde{\tau}_2^-$	177	$\tilde{\chi}_i^0\tau^-$	0.47

The LFV signal comes from the following processes ($i = 2,3$)

$$e^+e^- \;\to\; \tilde{\ell}_i^- \tilde{\ell}_i^+ \to \tau^+\mu^- \tilde{\chi}_1^0\tilde{\chi}_1^0 \,, \tag{10}$$

$$e^+e^- \;\to\; \tilde{\nu}_i\tilde{\nu}_i^c \to \tau^+\mu^- \tilde{\chi}_1^+\tilde{\chi}_1^- \,, \tag{11}$$

$$e^+e^- \;\to\; \tilde{\chi}_2^+\tilde{\chi}_1^- \to \tau^+\mu^- \tilde{\chi}_1^+\tilde{\chi}_1^- \,, \tag{12}$$

$$e^+e^- \;\to\; \tilde{\chi}_2^0\tilde{\chi}_1^0 \to \tau^+\mu^- \tilde{\chi}_1^0\tilde{\chi}_1^0 \,, \tag{13}$$

where $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 f\bar{f}'$, and $\tilde{\chi}_1^0$ escapes detection. The signature, therefore, would be $\tau^\pm\mu^\mp$ + 4 jets + $\not\!\!E_T$, $\tau^\pm\mu^\mp + \ell$ + 2 jets + $\not\!\!E_T$, or $\tau^\pm\mu^\mp + \not\!\!E_T$, depending on hadronic or leptonic $\tilde{\chi}_1^\pm$ decay mode. If both charginos are required to decay hadronically, the signal $\tau^\pm\mu^\mp$+4 jets+$\not\!\!E_T$ comes from (11), (12) and (13) and is SM-background free. The flavour-conserving processes analogous to (11–13), but with two τ's in the final state where one of the τ's decays leptonically to μ, contribute to the background. On the other hand, if jets are allowed to overlap, an important SM background to the final states with $\tau^\pm\mu^\mp + \geq 3jets + \not\!\!E_T$ comes from $e^+e^- \to t\bar{t}g$.

The results of a simple parton level simulation with a number of kinematic cuts listed in [14] is shown in Fig. 1. The significance is given by $\sigma_d = N/\sqrt{N+B}$ where N and B is the number of signal and background events, respectively, for a given luminosity. Fig. 1 shows the region (to the right of the curve) in the $\Delta m_{23} - \sin 2\theta_{23}$ plane that can be explored or ruled out at a 3σ level by the linear collider of energy 500 GeV for the given integrated luminosity. The contour (A) is for 500 fb^{-1} and (B) for 1000 fb^{-1}, whereas the dashed line (C) shows the reach of the process $\tilde{\nu}_i\tilde{\nu}_i^c$ alone (which were previously studied in [10,13]) using our cuts and assuming luminosity of 500 fb^{-1}. Comparing the dashed line with line (A) it has been concluded in Ref. [14] that the chargino contribution increases the sensitivity range to $\sin^2\theta_{23}$ by 10–20% while the sensitivity to Δm_{23} does not change appreciably.

In the same figure the contour lines for constant branching ratios of $\tau \to \mu\gamma$ are shown for comparison. In the limit of small mass splitting, the BR($\tau \to \mu\gamma$) can be calculated in the flavour basis using the mass insertion technique [18]. The LFV charged lepton radiative decay takes place through one or more slepton mass insertions, each bringing a factor of $\delta_{\alpha\beta}^{MN} = (M_{\tilde{l}}^2)_{\alpha\beta}^{MN}/\bar{m}_{\tilde{l}}^2$, where $(M_{\tilde{l}}^2)_{\alpha\beta}^{MN}$ with $M,N =$L, R are off-diagonal elements of the slepton mass matrix. In our 2–3 intergeneration mixing and using (4), the radiative process $\tau \to \mu\gamma$, therefore, constrains

$$\delta_{\mu\tau} = \frac{\Delta m_{23}}{\bar{m}_\nu} \sin 2\theta_{23} \,. \tag{14}$$

The contours in Fig. 1 have been obtained from the approximate formula of Ref. [19], normalised to the current experimental limit,

$$\mathrm{BR}(\tau \to \mu\gamma) \sim 1.1 \times 10^{-6} \max \left[\left(\frac{\delta^{\mathrm{LL}}_{\mu\tau}}{1.4} \right)^2, \left(\frac{\delta^{\mathrm{LR}}_{\mu\tau}}{8.3 \times 10^{-3}} \right)^2 \right] \left(\frac{100\,\mathrm{GeV}}{\bar{m}_\nu} \right)^4, \tag{15}$$

which serves only as an order of magnitude estimate of an upper limit for the supersymmetric contribution to the radiative lepton decay corresponding to the point in the $\Delta m_{23} - \sin 2\theta_{23}$ plane. The exact result, which is sensitive to the details of mass spectra and mixings, can in fact be much smaller due to cancellations among different contributions. Nevertheless, even if cancellations do not occur, Fig. 1 demonstrates that information from the slepton production and decay is very competitive and, in particular, can help to explore small Δm_{23} region.

To conclude: If super-partners are discovered, lepton flavour violating processes can be observed in slepton production and decay processes at future colliders. We have demonstrated that their analysis at e^+e^- collisions provides an opportunity to look for τ–μ flavour violation and that it is largely complementary to the search for $\tau \to \mu\gamma$. Although the discussion has been done in a specific model, the analysis has been phrased in as model-independent way as possible, and can easily be applied to cases with different slepton mixing patterns. The observation (or non-observation) of such processes would provide important clues about the flavour structure.

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