

# Supersymmetric Lepton Flavour Violation

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In supersymmetric models new sources of lepton flavour violation (LFV) may enhance the rates of charged lepton flavour violating processes, like  $\mu \rightarrow e\gamma$ , and generate distinct final states at future colliders, e.g.  $\tau\mu + jets + \cancel{E}_T$ . We discuss the role of chargino pair production for the LFV signals at  $e^+e^-$  colliders.

## I. INTRODUCTION

The neutrino experiment results [1] have a natural interpretation in terms of neutrino oscillations. This phenomenon is violating the individual lepton flavour number, and raises an interesting possibility of observing processes with charged-lepton flavour violation, like  $\mu \rightarrow e\gamma$ ,  $\tau \rightarrow \mu\gamma$ ,  $\mu$ - $e$  conversion in nuclei, rare  $K$  decays etc. Unfortunately, due to smallness of the neutrino masses, the predicted branching ratios for these processes are so tiny that they are completely unobservable, e.g.  $\text{BR}(\mu \rightarrow e\gamma) < 10^{-50}$ .

In the supersymmetric extension of the Standard Model, however, the situation may be quite different. In addition to the SM mechanism, new sources of lepton flavour violation (LFV) can be generated by non-diagonal soft supersymmetry breaking slepton mass terms. Even if the off-diagonal slepton mass terms are assumed to vanish at tree level to avoid the supersymmetric flavour-changing problem, they can be induced radiatively [2] in the framework of a seesaw mechanism by the right-handed heavy neutrinos. In such a case a substantial  $\nu_\mu - \nu_\tau$  mixing leads to [3, 4] large  $\tilde{\mu}_L - \tilde{\tau}_L$  and  $\tilde{\nu}_\mu - \tilde{\nu}_\tau$  mixings. As a result, the rates for rare processes, such as  $\mu \rightarrow e\gamma$ , can be substantially enhanced. For nearly degenerate sleptons, however, 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.

Once superpartners are discovered, it will also be possible to probe lepton flavour violation directly in their production and decay processes [5]. It has been demonstrated that sneutrino or charged slepton pair production at future  $e^+e^-$  (and/or  $\mu^+\mu^-$ ) colliders may provide a more powerful tool to search for supersymmetric lepton flavour violation (SLFV) than rare decay processes [3, 6]. However, sneutrinos and charged sleptons may not only be directly pair-produced in  $e^+e^-$  collisions, but can also be decay products of other supersymmetric particles, like charginos and neutralinos, decaying via cascades. We find that off-diagonal chargino pair-production, overlooked earlier, can make a significant contribution to the SLFV signal [7].

## II. COLLIDER SIGNALS OF SUPERSYMMETRIC LEPTON FLAVOUR VIOLATION

A flavor-violating signal is generated by the production of real sleptons, followed by their oscillation into a different flavored slepton, and subsequent decay to a lepton. For example, at  $e^+e^-$  colliders events with

$$\tau\mu + 4j + \cancel{E}_T, \quad \tau\mu l + 2j + \cancel{E}_T, \quad \tau\mu\bar{l} + 2j + \cancel{E}_T \quad (1)$$

can be expected. Searching for such signals has several advantages: first these processes are at tree level while rare decays are generated by loop corrections. Second, the SLFV processes in decays of sleptons are suppressed only as  $\Delta m_{\tilde{l}}/\Gamma_{\tilde{l}}$  [8], where  $\Gamma_{\tilde{l}}$  is the slepton decay width, as compared to the  $\Delta m_{\tilde{l}}/\bar{m}_{\tilde{l}}$  for rare decays. Since  $\bar{m}_{\tilde{l}}/\Gamma_{\tilde{l}}$  is typically of the order  $10^2$ – $10^3$ , one may expect spectacular signals for possible discovery in future  $e^+e^-$ ,  $\mu^+\mu^-$  or  $pp$  collider experiments. Last, but not least, the SM background with two or more leptons with different flavours is quite small.

At  $e^+e^-$  linear colliders the SLFV signals can be looked for in decays of sleptons which are produced in pairs,

$$\begin{aligned} e^+e^- &\rightarrow \tilde{\ell}_i^- \tilde{\ell}_i^+ \rightarrow \tau^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0, \\ e^+e^- &\rightarrow \tilde{\nu}_i \tilde{\nu}_i^c \rightarrow \tau^+ \mu^- \tilde{\chi}_1^+ \tilde{\chi}_1^-, \end{aligned} \quad (2)$$

with  $i = 1, 2, 3$ . These processes have been discussed in detail, showing that they may be competitive to rare decay processes in searches for SLFV signals [3, 6].

However, if the chargino  $\tilde{\chi}_2^\pm$  is not much heavier, as is the case in a substantial region of the MSSM parameter space, then off-diagonal chargino or neutralino pair production  $e^+e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ ,  $\tilde{\chi}_1^0 \tilde{\chi}_2^0$  can take place for the linear collider CM energy  $\sqrt{s} = 500$ – $800$  GeV. The heavier chargino and/or neutralino can decay via the SLFV chain,

$$e^+e^- \rightarrow \tilde{\chi}_2^+ \tilde{\chi}_1^- \rightarrow \tau^+ \mu^- \tilde{\chi}_1^+ \tilde{\chi}_1^-, \quad (3)$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \tau^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0, \quad (4)$$

where  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 f \bar{f}'$ , and  $\tilde{\chi}_1^0$  escapes detection. The signature therefore would be the same as in slepton pair production, *i.e.* eq.(1), depending on hadronic or leptonic  $\tilde{\chi}_1^\pm$  decay mode. As a result, the processes (3) and (4) provide a new source for the signal in addition to those discussed in Ref.[6].

### III. THE ROLE OF CHARGINOS

To illustrate the role of charginos for the SLFV process at an  $e^+e^-$  linear collider, such as the proposed TESLA [9], we consider the signal and background rates for two representative points in the MSSM parameter space. These points are given in terms of mSUGRA scenarios defined by:

$$\begin{aligned} RR1 : m_0 &= 100; \quad M_{1/2} = 200; \quad A_0 = 0; \quad \tan \beta = 3; \quad \text{sgn}(\mu) = + \\ RR2 : m_0 &= 160; \quad M_{1/2} = 200; \quad A_0 = 600; \quad \tan \beta = 30; \quad \text{sgn}(\mu) = + \end{aligned} \quad (5)$$

chosen for detailed case studies at the ECFA/DESY linear collider workshop. Here the masses and  $A_0$  are in GeV, and standard notation is used. The corresponding masses of chargino, neutralino and slepton states relevant for SLFV processes at  $\sqrt{s} = 500$  and 800 GeV, along with some branching ratios, can be found in [7].

To be more specific, we take a pure 2-3 intergeneration mixing between  $\tilde{\nu}_\mu$  and  $\tilde{\nu}_\tau$ , generated by a near-maximal mixing angle  $\theta_{23}$ , and ignore any mixings with  $\tilde{\nu}_e$ . The scalar neutrino mass matrix  $m_{\tilde{\nu}}^2$ , restricted to the 2-3 generation subspace, can be written in the fermion mass-diagonal basis as

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} \cos \theta_{23} & -\sin \theta_{23} \\ \sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} m_{\tilde{\nu}_2} & 0 \\ 0 & m_{\tilde{\nu}_3} \end{pmatrix} \begin{pmatrix} \cos \theta_{23} & \sin \theta_{23} \\ -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}, \quad (6)$$

where  $m_{\tilde{\nu}_2}$  and  $m_{\tilde{\nu}_3}$  are the physical masses of  $\tilde{\nu}_2$  and  $\tilde{\nu}_3$  respectively. In the following we take the mixing angle  $\theta_{23}$  and  $\Delta m_{23} = |m_{\tilde{\nu}_2} - m_{\tilde{\nu}_3}|$  as free, independent parameters.

In the case of RR2 the lightest chargino decays only leptonically (without SLFV it decays into  $\chi_1^0 \tau \nu_\tau$ ). As a result, the signature of SLFV in  $\tilde{\chi}_2^\pm \tilde{\chi}_1^\mp$  production would be one muon and three taus plus missing energy. Such a signal might be extremely difficult to extract from background with four taus or with two muons and two taus for realistic tau identification efficiencies.

For the case RR1, however, the lightest chargino has a large branching ratio for hadronic decays. Therefore in our analyses we consider only their hadronic decay modes. Given the mass spectrum, the off-diagonal  $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$  pair is the only possibility for the SLFV signal in chargino production at  $\sqrt{s} = 500$  GeV. The slepton flavour violation can occur in the heavier chargino  $\tilde{\chi}_2^\mp$  cascade decay chain as shown

$$\begin{aligned} [S1] \quad e^+e^- &\rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp, & \tilde{\chi}_2^+ &\rightarrow \tau^+ \tilde{\nu}_{2,3}, & \tilde{\nu}_{2,3} &\rightarrow \mu^- \tilde{\chi}_1^+ \\ [S2] \quad e^+e^- &\rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp, & \tilde{\chi}_2^+ &\rightarrow \mu^+ \tilde{\nu}_{2,3}, & \tilde{\nu}_{2,3} &\rightarrow \tau^- \tilde{\chi}_1^+ \end{aligned}$$

followed by  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + q + \bar{q}'$ . There is another sequence with the charges reversed. The other process for the same final state, which was discussed in [6], is the following

$$[S3] \quad e^+e^- \rightarrow \tilde{\nu}_i \tilde{\nu}_i^c, \quad \tilde{\nu}_i \rightarrow \tilde{\chi}_1^- \tau^+, \quad \tilde{\nu}_i^c \rightarrow \tilde{\chi}_1^+ \mu^-$$

where  $i = 2, 3$ . In [S1] and [S2] the slepton flavour violating decay occurs in two ways leading to the the same final state so that eventually the signal rate gets doubled. The background may originate from the flavour-conserving SUSY processes

$$\begin{aligned} [B1] \quad e^+e^- &\rightarrow \tilde{\chi}_2^+ \tilde{\chi}_1^-, & \tilde{\chi}_2^+ &\rightarrow \tau^+ \tilde{\nu}_\tau, & \tilde{\nu}_\tau &\rightarrow \tau^- (\rightarrow \mu^-) \tilde{\chi}_1^+ \\ [B2] \quad e^+e^- &\rightarrow \tilde{\chi}_2^+ \tilde{\chi}_1^-, & \tilde{\chi}_2^+ &\rightarrow \tau^+ (\rightarrow \mu^+) \tilde{\nu}_\tau, & \tilde{\nu}_\tau &\rightarrow \tau^- \tilde{\chi}_1^+ \\ [B3] \quad e^+e^- &\rightarrow \tilde{\nu}_i \tilde{\nu}_i^c, & \tilde{\nu}_i &\rightarrow \tilde{\chi}_1^- \tau^+, & \tilde{\nu}_i^c &\rightarrow \tilde{\chi}_1^+ \tau^- (\rightarrow \mu^-) \\ [B4] \quad e^+e^- &\rightarrow \tilde{\tau}_2^+ \tilde{\tau}_2^-, & \tilde{\tau}_2^+ &\rightarrow \tau^+ \tilde{\chi}_2^0, & \tilde{\chi}_2^0 &\rightarrow \tilde{\chi}_1^0 \tau^+ (\rightarrow jets) \tau^- (\rightarrow \mu^-), & \tilde{\tau}_2^- &\rightarrow \nu_\tau \tilde{\chi}_1^- \end{aligned}$$

in which the  $\mu$  comes from  $\tau$  decay after the  $\tau\tau X$  events are produced, and from an important SM background

$$[B5] \quad e^+e^- \rightarrow t\bar{t}g$$

with semileptonic top decays if two quark jets are allowed to overlap. At 800 GeV additional signal and background channels open [7].

With the set of kinematical cuts to enhance the signal processes (listed in [7]), in Fig.1 the contour lines are plotted for the significance  $\sigma_d = \frac{N}{\sqrt{N+B}}$ , where N and B is the number of signal and background events respectively for a given luminosity. Comparing the dashed line with line B in Fig.1 we see that that the chargino contribution [S1] and [S2] increases the sensitivity range to  $\sin^2 \theta_{23}$  by 10-20% while the sensitivity to  $\Delta m_{23}$  does not change appreciably. At 800 GeV the background is more important reducing the sensitivity to the SLFV signal.

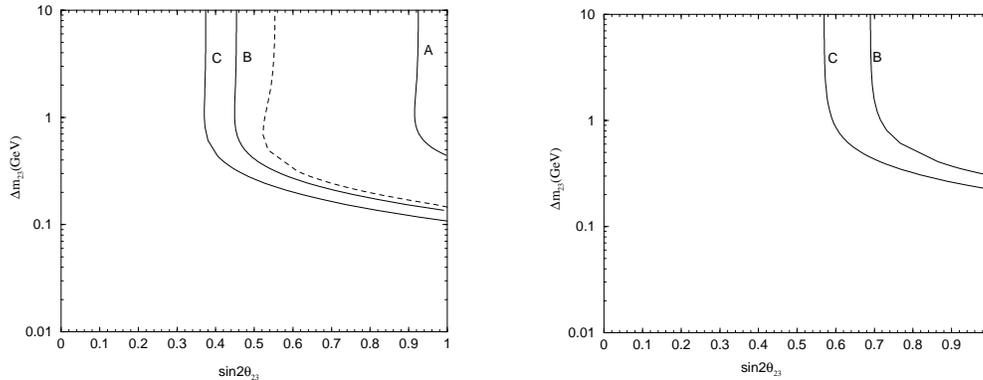


FIG. 1: *left: The significance contours for the SUSY point RR1 in  $\Delta m_{23} - \sin 2\theta_{23}$  plane for  $\sqrt{s} = 500$  GeV and for different luminosity options, contours A, B and C being for  $50 \text{ fb}^{-1}$ ,  $500 \text{ fb}^{-1}$  and  $1000 \text{ fb}^{-1}$ , respectively. The dashed line is for only  $\tilde{\nu}\tilde{\nu}^c$  contribution with luminosity  $500 \text{ fb}^{-1}$ . The upper-right side of these contours can be explored or ruled out at the  $3\sigma$  level.*

*right: The same for  $\sqrt{s} = 800$  GeV and two luminosities  $500 \text{ fb}^{-1}$  and  $1000 \text{ fb}^{-1}$*

#### IV. CONCLUSIONS

Neutrino oscillations imply the violation of individual lepton flavour numbers and raise an interesting possibility of observing processes with a violation of lepton flavour between two charged leptons. In supersymmetry LFV processes may substantially be enhanced and many interesting signals of SLFV processes may be expected at future colliders. Our discussion of chargino contribution shows that a detailed account of all possible production channels is needed in assessing the sensitivity of future colliders to SLFV.

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- [1] R. J. Davis, D. S. Harmer and K. C. Hoffman, Phys. Rev. Lett. **20** (1968) 1205; S. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **86** (2001) 5656 [arXiv:hep-ex/0103033], Phys. Rev. Lett. **85** (2000) 3999 [arXiv:hep-ex/0009001]; Q. R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. **87** (2001) 071301.
  - [2] F. Borzumati and A. Masiero, Phys. Rev. Lett. **57** (1986) 961; L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. B **267** (1986) 415; J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi and T. Yanagida, Phys. Lett. B **357** (1995) 579.
  - [3] N. Arkani-Hamed, J. L. Feng, L. J. Hall and H. Cheng, Phys. Rev. Lett. **77** (1996) 1937 [hep-ph/9603431].
  - [4] J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D **53** (1996) 2442 [hep-ph/9510309].
  - [5] N. V. Krasnikov, Mod. Phys. Lett. A **9** (1994) 791.
  - [6] J. Hisano, M. M. Nojiri, Y. Shimizu and M. Tanaka, Phys. Rev. D **60** (1999) 055008 [hep-ph/9808410].
  - [7] M. Guchait, J. Kalinowski and P. Roy, Eur. Phys. J. C **21** (2001) 163 [arXiv:hep-ph/0103161].
  - [8] N. Arkani-Hamed, J. L. Feng, L. J. Hall and H. Cheng, Nucl. Phys. B **505** (1997) 3 [hep-ph/9704205].
  - [9] J. A. Aguilar-Saavedra *et al.* [ECFA/DESY LC Physics Working Group], arXiv:hep-ph/0106315.