Impact of slepton generation mixing on the search for sneutrinos

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Contents

1. Introduction

(1) Motivation;

- *Why SUSY?;*

  In the Minimal Supersymmetric Standard Model (MSSM)
  SUSY partners of all Standard Model (SM) particles with masses less than O(1 TeV) are introduced.
  This solves the problems of hierarchy, fine-tuning and naturalness of the SM.

- *Hence discovery of all SUSY partners and study of their properties are essential for testing the MSSM.*

- *Here we focus on SUSY partners of neutrinos (i.e sneutrinos).*

- *Systematic study of sneutrino decays including bosonic decays such as sneutrino -> slepton H^+/W^+ in the MSSM without LFV in slepton sector has been performed already.*

  (ex) A. Bartl et al., Phys. Lett. B 460 (1999) 157;
  A. Bartl et al., Phys. Lett. B 538 (2002) 137 [hep-ph/0204071];
  A. Bartl et al., Phys. Rev. D 66 (2002) 115009 [hep-ph/0207186]

- *Study of slepton production and decays in the MSSM with LFV has been performed .*

  (ex) N. V. Krasnikov, Phys. Lett. B388 (1996) 783 [hep-ph/9511464];
  N. Arkani-Hamed, H. C. Cheng, J. L. Feng and L. J. Hall, Phys. Rev. Lett. 77 (1996) 1937 [hep-ph/9603431];
  J. Hisano et al. Phys. Rev. D60 (1999) 055008 [hep-ph/9808410];
  D. Nomura, Phys. Rev. D64 (2001) 075001 [hep-ph/0004256];
  W. Porod and W. Majerotto, Phys. Rev. D 66 (2002) 015003 [hep-ph/0201284];
  N. Oshimo, Eur.Phys.J. C39 (2005) 383 [hep-ph/0409018]

- ***However, systematic study of sneutrino decays including both fermionic and bosonic decays in the MSSM with LFV has not been performed yet.***

- ***Systematic study of sneutrino decays in the MSSM with LFV will be performed in this work.***

(2)Purpose of this work;

- *In this work we perform systematic study of sneutrino decays in the general MSSM with LFV in slepton sector.*

- *We show that branching ratios of LFV sneutrino decays due to slepton generation mixing can be sizable in a significant part of the MSSM parameter space despite the very strong experimental limits on LFV processes.*

- *This could have an important impact on the search for sneutrinos and the MSSM parameter determination in the future colliders, such as LHC, ILC, CLIC and muon collider.*

2. MSSM with LFV

- *The basic parameters of the MSSM with LFV:*

$$\{\tan\beta, m_{H^+}, M_2, \mu, M^2_{L,\alpha\beta}, M^2_{E,\alpha\beta}, A_{\alpha\beta}\} \text{ (at weak scale)}$$

$$(\alpha,\beta = 1,2,3 = e,\mu,\tau)$$

$\tan\beta$: ratio of VEV of the two Higgs doublets $\langle H^0{}_2\rangle / \langle H^0{}_1\rangle$

M_2: SU(2) gaugino mass

μ : higgsino mass parameter

$M^2_{L,\alpha\beta}$: left slepton soft mass matrix

$M^2_{E,\alpha\beta}$: right slepton soft mass matrix

$A_{\alpha\beta}$: trilinear coupling matrix of sleptons and a Higgs boson

$(\alpha,\beta = 1,2,3 = e,\mu,\tau)$

- ***Here we study $\tilde{\mu}-\tilde{\tau}$ mixing case.***

LFV parameters in our study are:

$M^2_{L,23}$: $\tilde{\mu}_L - \tilde{\tau}_L$ *mixing term* ($\tilde{\nu}_\mu - \tilde{\nu}_\tau$ *mixing term*)

$M^2_{E,23}$: $\tilde{\mu}_R - \tilde{\tau}_R$ *mixing term*

A_{23} : $\tilde{\mu}_L - \tilde{\tau}_R$ *mixing term*

A_{32} : $\tilde{\mu}_R - \tilde{\tau}_L$ *mixing term*

- ***(note) We assume that all the basic parameters are real.***

- ***(note) The basic parameters determine all of the physics here.***

- ***Charged Slepton Mass Matrix:***

The most general charged slepton mass matrix including left-right mixing as well as flavour mixing in the basis of $(\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)$ ***is given by:***

$$\begin{array}{c} (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L), (\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R) \\ M_{\tilde{l}}^2 = \begin{pmatrix} M_{LL}^2 & M_{RL}^{2\,\dagger} \\ M_{RL}^2 & M_{RR}^2 \end{pmatrix} \end{array}$$

with

$$M_{LL,\alpha\beta}^2 = M_{L,\alpha\beta}^2 + (D_L^{\tilde{l}} + F_\alpha)\delta_{\alpha\beta}$$

$$M_{RR,\alpha\beta}^2 = M_{E,\alpha\beta}^2 + (D_R^{\tilde{l}} + F_\alpha)\delta_{\alpha\beta}$$

$$M_{RL,\alpha\beta}^2 = v_1 A_{\beta\alpha} - m_{l_\alpha}\mu^* \tan\beta\,\delta_{\alpha\beta} \quad (v_1 = \langle H_1^0 \rangle)$$

$(\alpha, \beta = 1, 2, 3 = e, \mu, \tau)$

- ***Masses and mixings of the sleptons:***

$$R^{\tilde{\ell}} M_{\tilde{\ell}}^2 R^{\tilde{\ell}\dagger} = \mathrm{diag}(m_{\tilde{\ell}_1}^2, \ldots, m_{\tilde{\ell}_6}^2)$$

$$m_{\tilde{\ell}_i} < m_{\tilde{\ell}_j} \text{ for } i < j$$

$$\tilde{l}_i = R^{\tilde{l}}_{i\alpha} \tilde{l}'_\alpha$$ ***(Mass eigenstates)***

$$\tilde{l}_i = (\tilde{l}_1, \ldots\ldots\ldots\ldots, \tilde{l}_6)$$

$$\tilde{l}'_\alpha = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)$$

- ***Sneutrino Mass Matrix*:**

The most general sneutrino mass matrix with flavor mixing in the basis of

$(\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)$ ***is given by:***

$$M^2_{\tilde{\nu}} = \begin{pmatrix} M^2_{\tilde{\nu}LL} \end{pmatrix}^{(\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)}$$

with

$$M^2_{\tilde{\nu}LL,\alpha\beta} = M^2_{L,\alpha\beta} + D^{\tilde{\nu}}_L \delta_{\alpha\beta}$$

$(\alpha, \beta = 1, 2, 3 = e, \mu, \tau)$

- ***Masses and mixings of the sneutrinos:***

$$R^{\tilde{\nu}} M_{\tilde{\nu}}^2 R^{\tilde{\nu}-1} = \begin{pmatrix} m_{\tilde{\nu}_1}^2 & 0 & 0 \\ 0 & m_{\tilde{\nu}_2}^2 & 0 \\ 0 & 0 & m_{\tilde{\nu}_3}^2 \end{pmatrix}$$

$$(m_{\tilde{\nu}_1} < m_{\tilde{\nu}_2} < m_{\tilde{\nu}_3})$$

$$\tilde{\nu}_i = R_{i\alpha}^{\tilde{\nu}} \tilde{\nu}'_\alpha$$ (Mass eigenstates)

$$\tilde{\nu}_i = (\tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$$

$$\tilde{\nu}'_\alpha = (\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)$$

3. *Constraints on the MSSM*

The following constraints are imposed in our analysis in order to respect experimental and theoretical constraints:

(a) Vacuum stability conditions

(see J.A. Casas and S. Dimopoulos, Phys. Lett. B 387 (1996) 107 [hep-ph/9606237].)

(ex) $|A_{23}|^2 < h_\tau^2 (M_{L,22}^2 + M_{E,33}^2 + m_1^2)$ ***etc.***

with $m_1^2 = (m_{H^+}^2 + m_Z^2 \sin^2\theta_W)\sin^2\beta - \frac{1}{2} m_Z^2$

(b) LEP limits on sparticle masses

(ex) $m_{\tilde{\chi}_1^+} > 103\,GeV$ ***etc.***

(c) lepton (g-2) limits

(ex) experimental limit on SUSY contribution to muon (g-2) etc.

(see F. Jegerlehner, hep-ph/0703125)

(d) Experimental limits on LFV lepton decay branching ratios

(ex)

$B(\tau^- \to \mu^-\gamma) < 4.5\cdot 10^{-8}$ ***(Belle exp.)***

$B(\tau^- \to e^-\gamma) < 1.1\cdot 10^{-7}$ ***(Babar exp.)***

$B(\mu^- \to e^-\gamma) < 1.2\cdot 10^{-11}$ ***(MEGA exp.)***

$B(\tau^- \to \mu^-\mu^+\mu^-) < 2.0\cdot 10^{-7}$ ***(Belle exp.)*** ***etc.***

(e) The constraint on m_{H^+} and tanβ from the experimental data on $B(B_u^- \to \tau^- \bar{\nu}_\tau)$ from BELLE exp.

(see Belle Coll., hep-ex/0604018v3; W.S. Hou, Phys.Rev. D48(1993) 2342)

(ex) $|R_{B\tau\nu}^{SUSY} - 1.13| < 1.0$ **(95% CL).**

$$R_{B\tau\nu}^{SUSY} = B^{SUSY}(B_u^- \to \tau^- \bar{\nu}_\tau) / B^{SM}(B_u^- \to \tau^- \bar{\nu}_\tau) = \left| 1 - \left(\frac{m_{B^+} \tan\beta}{m_{H^+}} \right)^2 \right|^2$$

(Note) We find that these constraints are very important:

- *Vacuum stability conditions* ➡ *strongly constrain trilinear couplings* $A_{\alpha\beta}$
- *muon (g-2) limit* ➡ *strongly disfavours negative* μ *region*
- $B(\tau^- \to \mu^- \gamma)$ *limit* ➡ *strongly constrains the LFV slepton parameters*
- $B(B_u^- \to \tau^- \bar{\nu}_\tau)$ *data* ➡ *strongly constrain (* m_{H^+}*, tan*β*)*

4. LFV Benchmark Scenario

We take the following $\tilde{\mu}-\tilde{\tau}$ mixing scenario as a LFV benchmark scenario:

$\tan\beta = 20,\ m_{H^+} = 150GeV,\ M_2 = 650GeV,\ \mu = 150GeV,$

$$M^2_{L,\alpha\beta} = \begin{pmatrix} (430)^2 & (1)^2 & (1)^2 \\ (1)^2 & (410)^2 & (61.2)^2 \\ (1)^2 & (61.2)^2 & (400)^2 \end{pmatrix} (GeV)^2$$

$\tilde{\mu}_L - \tilde{\tau}_L$ *mixing term*

$$M^2_{E,\alpha\beta} = \begin{pmatrix} (230)^2 & (1)^2 & (1)^2 \\ (1)^2 & (210)^2 & (22.4)^2 \\ (1)^2 & (22.4)^2 & (200)^2 \end{pmatrix} (GeV)^2$$

$\tilde{\mu}_R - \tilde{\tau}_R$ *mixing term*

$$A_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 25 \\ 0 & 0 & 150 \end{pmatrix} (GeV)$$

$\tilde{\mu}_L - \tilde{\tau}_R$ *mixing term*

$\tilde{\nu}_1 \sim \tilde{\nu}_\tau$ $\tilde{\nu}_2 \sim \tilde{\nu}_\mu$ $\tilde{\nu}_3 \sim \tilde{\nu}_e$

$\tilde{l}_1^- \sim \tilde{\tau}_R^-$ $\tilde{l}_2^- \sim \tilde{\mu}_R^-$ $\tilde{l}_3^- \sim \tilde{e}_R^-$

$$m_{\tilde{\nu}_1} = 393GeV, m_{\tilde{\nu}_2} = 407GeV, m_{\tilde{\nu}_3} = 425GeV,$$

$$m_{\tilde{\ell}_1} = 204GeV, m_{\tilde{\ell}_2} = 215GeV, m_{\tilde{\ell}_3} = 234GeV,$$
$$m_{\tilde{\ell}_4} = 401GeV, m_{\tilde{\ell}_5} = 415GeV, m_{\tilde{\ell}_6} = 433GeV,$$

$$m_{\tilde{\chi}_1^\pm} = 147GeV, m_{\tilde{\chi}_2^\pm} = 661GeV,$$
$$m_{\tilde{\chi}_1^0} = 138GeV, m_{\tilde{\chi}_2^0} = 155GeV, m_{\tilde{\chi}_3^0} = 331GeV, m_{\tilde{\chi}_4^0} = 661GeV,$$

Our scenario is within the reach of LHC and ILC.

5. Impact of slepton generation mixing on sneutrino decays

Possible important sneutrino decays are:

- $\tilde{\nu}_i \to \nu \tilde{\chi}_j^0$ $\quad$ $\tilde{\nu}_i \to l_\alpha^- \tilde{\chi}_k^+$ ***(fermionic mode)***
- $\tilde{\nu}_i \to \tilde{l}_j^- W^+$ $\quad$ $\tilde{\nu}_i \to \tilde{l}_j^- H^+$ ***(bosonic mode)***

We study the effect of slepton generation mixing on these sneutrino decays.

- ***Sneutrino decay branching ratios in our scenario:***

In our scenario we have:

- $B(\tilde{\nu}_1 \to \mu^- \tilde{\chi}_1^+) = 1.4\%$ ***(LFV)***
- $B(\tilde{\nu}_1 \to \tau^- \tilde{\chi}_1^+) = 36\%$ ***(LFC)***

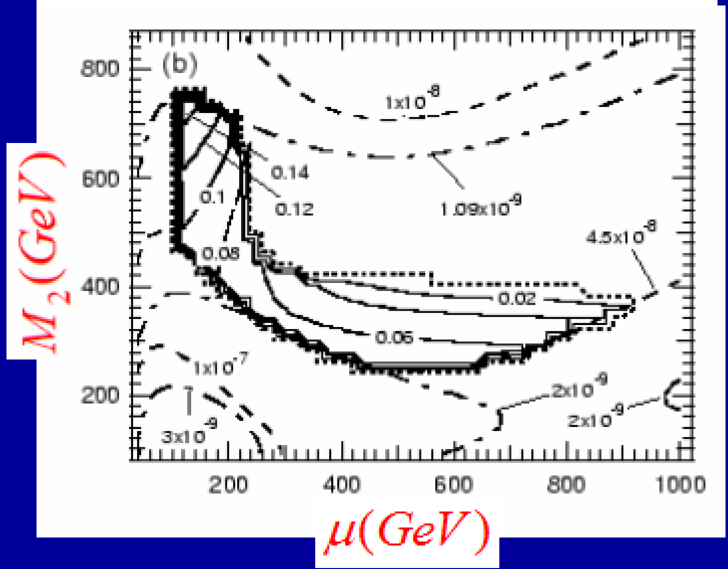
- $B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+) = 38\%$ ***(LFV)***
- $B(\tilde{\nu}_2 \to \tilde{l}_1^- W^+) = 0.3\%$ ***(LFV)***
- $B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+) = 12\%$ ***(LFV)***
- $B(\tilde{\nu}_2 \to \mu^- \tilde{\chi}_1^+) = 20\%$ ***(LFC)***

(note) $\tilde{\nu}_2 \sim \tilde{\nu}_\mu \quad , \quad \tilde{l}_1^- \sim \tilde{\tau}_R^-$

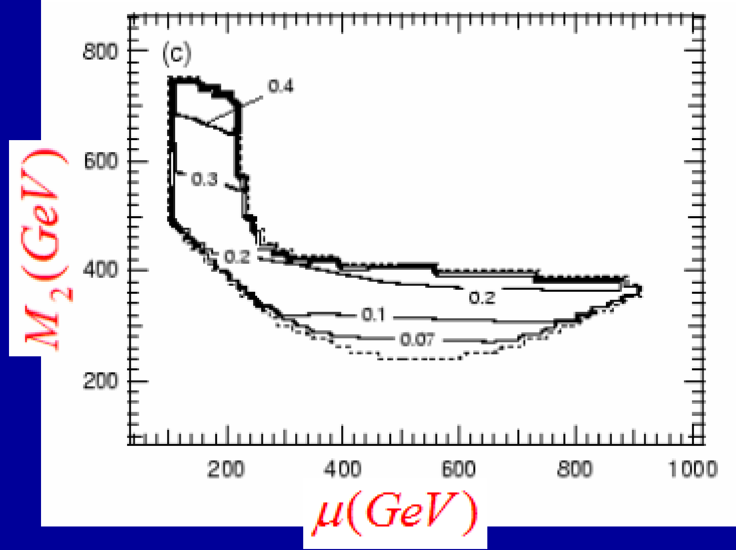
We have large LFV decay branching ratios!

Contour plots of LFV BR's in our scenario

$B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$ **contours**



$B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ **contours**



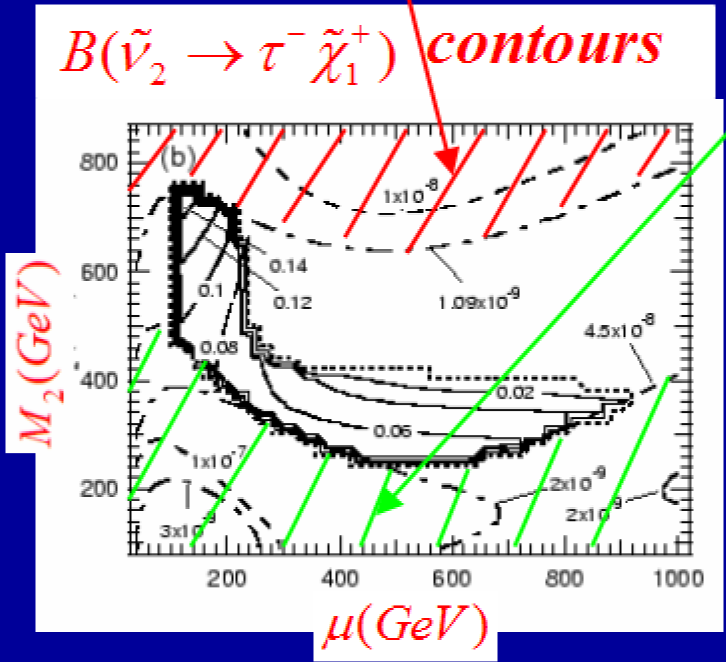
(note) $\tilde{\nu}_2 \sim \tilde{\nu}_\mu$, $\tilde{l}_1^- \sim \tilde{\tau}_R^-$

LFV BR's are large in a significant region of $\mu - M_2$ *plane in our scenario!*

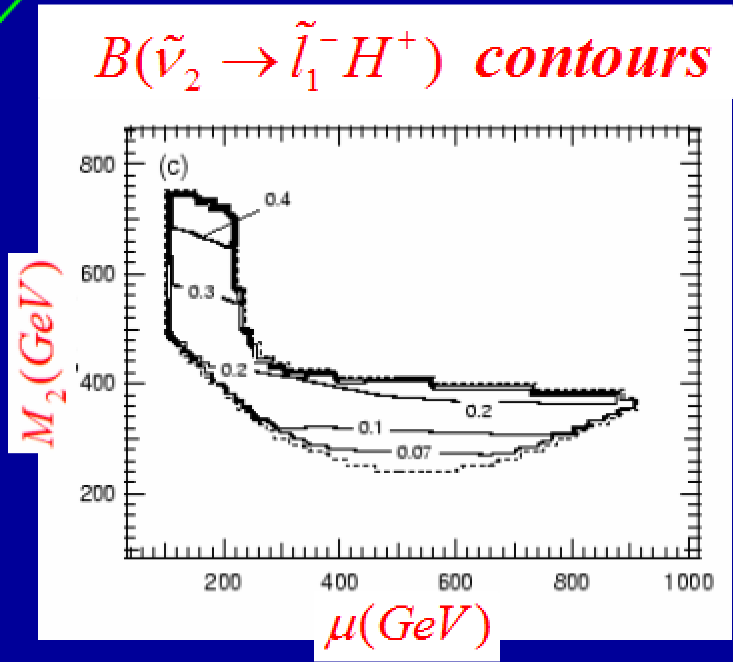
Contour plots of LFV BR's in our scenario

excluded by muon g-2 data *excluded by $B(\tau^- \to \mu^- \gamma)$ limit*

$B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$ **contours**



$B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ **contours**

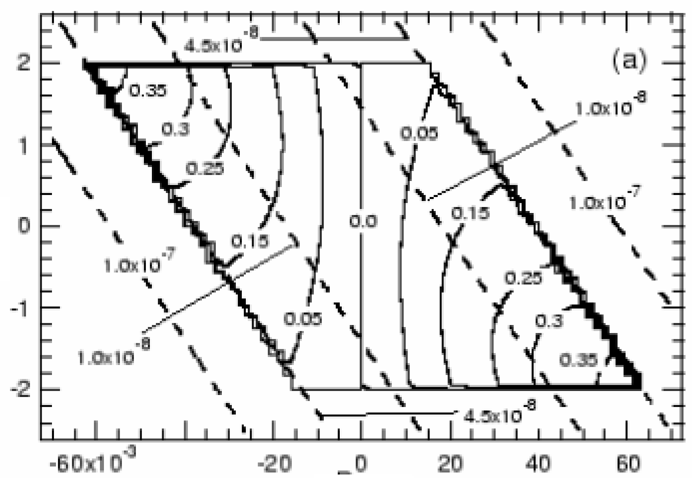


(note) $\tilde{\nu}_2 \sim \tilde{\nu}_\mu \;,\quad \tilde{l}_1^- \sim \tilde{\tau}_R^-$

LFV BR's are large in a significant region of $\mu - M_2$ plane in our scenario!

$B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$ ***contours***

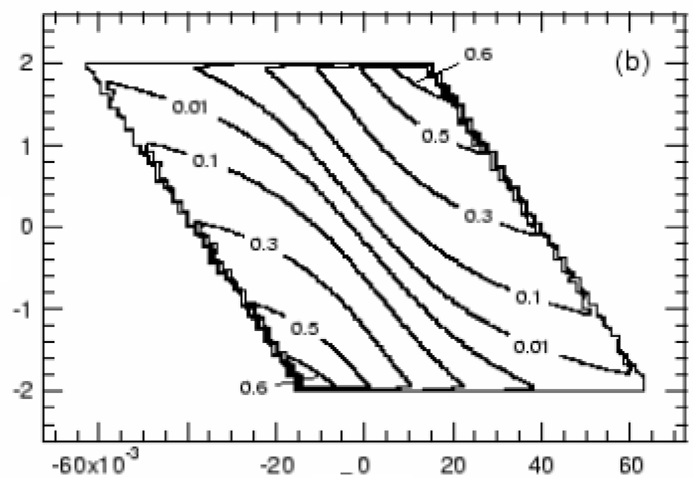
RA_{23}



R_{L23}

$B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ ***contours***

RA_{23}



R_{L23}

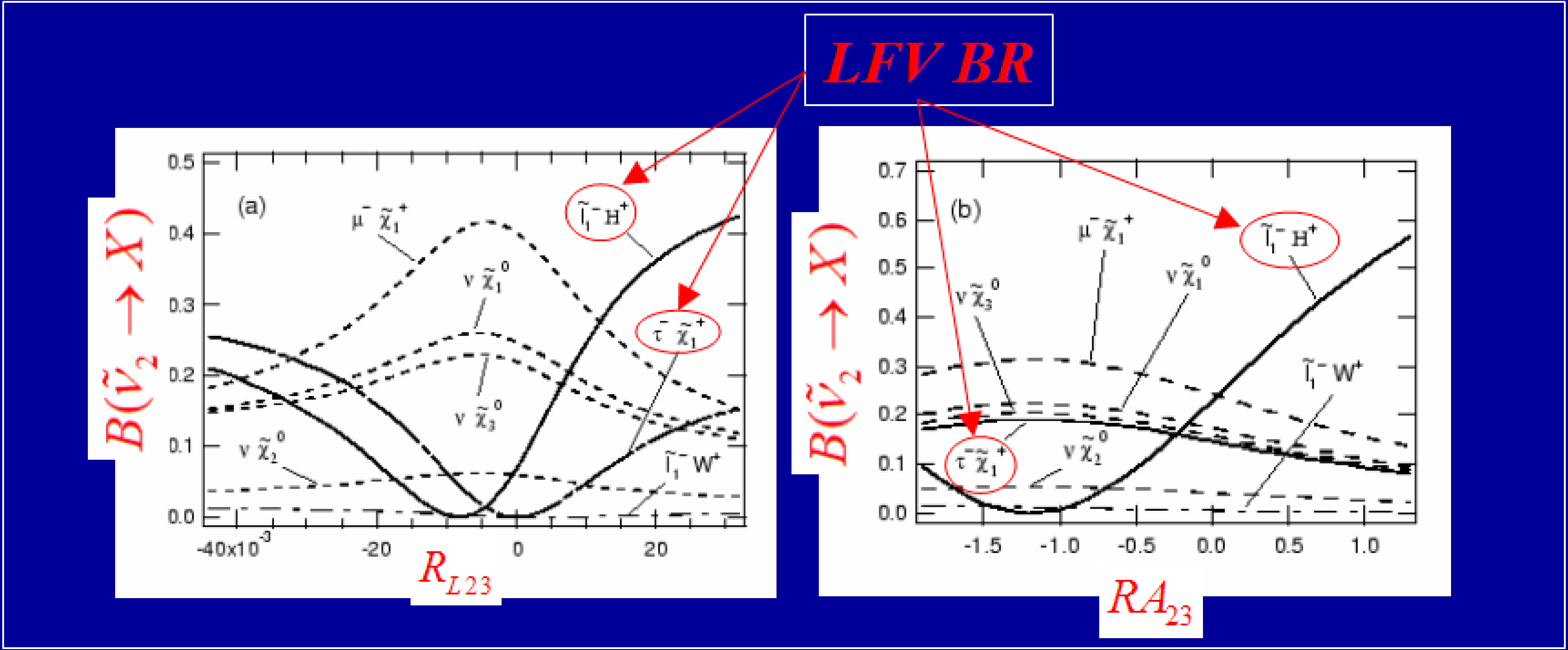
$R_{L23} = M^2_{L,23} / ((M^2_{L,11} + M^2_{L,22} + M^2_{L,33})/3)$; $RA_{23} = A_{23} / ((|A_{11}| + |A_{22}| + |A_{33}|)/3)$

$\tilde{\mu}_L - \tilde{\tau}_L$ ***mixing para.*** $\tilde{\mu}_L - \tilde{\tau}_R$ ***mixing para.***

(note) $\tilde{\nu}_2 \sim \tilde{\nu}_\mu$, $\tilde{l}_1^- \sim \tilde{\tau}_R^-$

- ***LFV BR's are large in a significant region of*** $R_{L23} - RA_{23}$ ***plane in our scenario!***
- $B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$ ***is sensitive to*** $\tilde{\mu} - \tilde{\tau}$ ***mixing para.*** R_{L23}***!***
- $B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ ***is sensitive to*** $\tilde{\mu} - \tilde{\tau}$ ***mixing paras.*** R_{L23} ***and*** RA_{23}***!***

R_{L23} and RA_{23} dependences of $\tilde{\nu}_2$ decay BR's



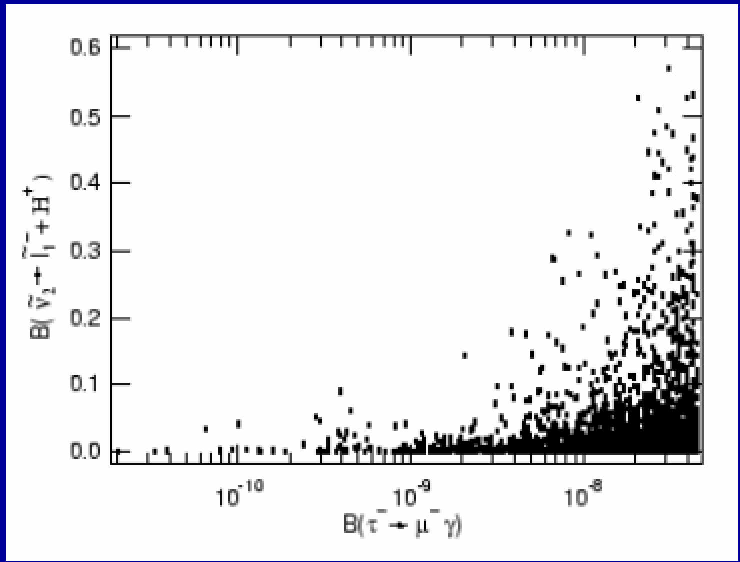
$\Downarrow$

LFV BR's $B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$ and $B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ can be *very large* and *very sensitive* to *LFV* parameters R_{L23} and (R_{L23}, RA_{23}) in our scenario, respectively!

Scatter Plot of LFV BR's in our scenario

There are strong correlations among the LFV sneutrino decays and the LFV tau decay (i.e. $\tau^- \to \mu^- \gamma$);

(ex) $B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ *v.s.* $B(\tau^- \to \mu^- \gamma)$



Scatter Plot for our scenario with the scatter parameters:
$0 < M_2 < 1000$ GeV
$|\mu| < 1000$ GeV
$|R_{L23}| < 0.1$
$|R_{E23}| < 0.2$
$|RA_{23}| < 2.5$
$|RA_{32}| < 2.5$

LFV BR $B(\tilde{\nu}_2 \to \tilde{l}_1^- H^+)$ ***can be large even if the present bound on*** $B(\tau^- \to \mu^- \gamma)$ ***improves by one order of magnitude!***

6. Discussion

1. Sneutrino decays in $\tilde{e}-\tilde{\tau}$ mixing case;

We have studied sneutrino decays in $\tilde{\mu}-\tilde{\tau}$ mixing case.
We have obtained similar results in $\tilde{e}-\tilde{\tau}$ mixing case.
This is mainly due to the fact that the experimental limit on $B(\tau^- \to e^-\gamma)$ is similar to that on $B(\tau^- \to \mu^-\gamma)$.

2. LFV production cross section;

In $\tilde{e}-\tilde{\tau}$ mixing case;

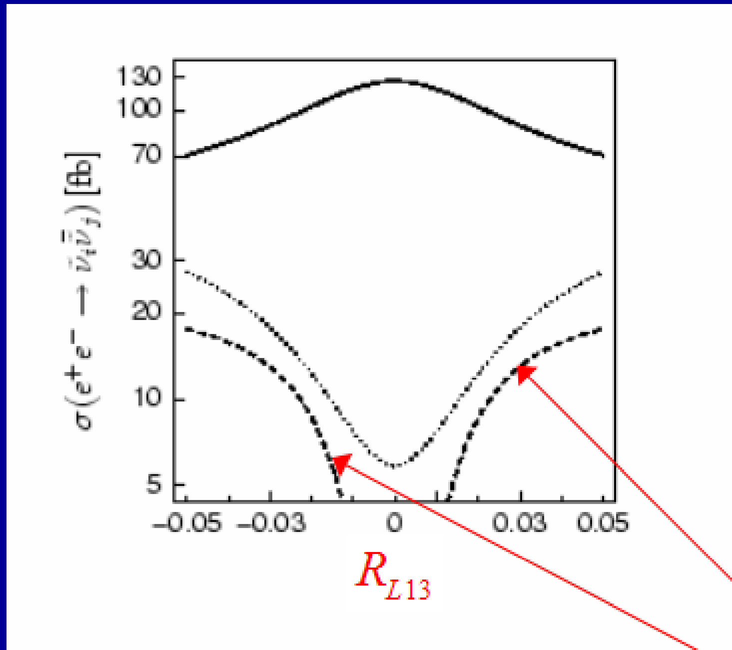
We can have large LFV production cross section $\sigma(e^+e^- \to \tilde{\nu}_1(\sim \tilde{\nu}_\tau)\bar{\tilde{\nu}}_3(\sim \bar{\tilde{\nu}}_e))$ due to chargino exchanges in t-channel!
This LFV cross section can be as large as ~17fb at ILC with $E_{CM} = 1TeV$ in a $\tilde{e}-\tilde{\tau}$ mixing version of our $\tilde{\mu}-\tilde{\tau}$ mixing scenario.
In this case the production cross sections are sensitive to the LFV parameter R_{L13} (i.e. $\tilde{\nu}_e-\tilde{\nu}_\tau$ mixing parameter). (see Fig.)

In $\tilde{\mu}-\tilde{\tau}$ mixing case;

We have no LFV production since the chargino exchanges can not contribute to LFV production in this case!
In this case the production cross sections are insensitive to the LFV parameters.

(note) Z^0 exchange in s-channel can not contribute to LFV production due to vanishing $Z^0-\tilde{\nu}_i-\bar{\tilde{\nu}}_j$ coupling for $i \neq j$.

$\tilde{e}-\tilde{\tau}$ *mixing case*



LFV prod. cross section

Figure 6: Production cross sections $\sigma(e^+e^- \to \tilde{\nu}_1\bar{\tilde{\nu}}_1)$ (dotted line), $\sigma(e^+e^- \to \tilde{\nu}_1\bar{\tilde{\nu}}_3)$ (dashed line) and $\sigma(e^+e^- \to \tilde{\nu}_3\bar{\tilde{\nu}}_3)$ (solid line) as a function of R_{L13}. The R_{L13} region shown in the figure is allowed by the current limit $B(\tau^- \to e^-\gamma) < 1.1 \times 10^{-7}$.

$$R_{L13} = M^2_{L,13} / ((M^2_{L,11} + M^2_{L,22} + M^2_{L,33})/3)$$

3. LFV signatures at ILC;

In experimental search for LFV in sneutrino decays it is important to have at least two different lepton flavour modes with sizable branching ratios in decay of a sneutrino; e.g. both sizable $B(\tilde{\nu}_2 \to \mu^- \tilde{\chi}_1^+)$ and sizable $B(\tilde{\nu}_2 \to \tau^- \tilde{\chi}_1^+)$.

In this case, we could have the following LFV signals :

$$e^+e^- \to \tilde{\nu}_2\bar{\tilde{\nu}}_2 \to \mu^-\tau^+\tilde{\chi}_1^+\tilde{\chi}_1^- \to \mu^-\tau^+ + 4\,jets + \not{E} \ .$$

4. LFV contributions to collider signatures;

For example, at ILC with E_{CM}=1TeV, $P_{e^-} = -90\%$, $P_{e^+} = 60\%$ we have in our $\tilde{\mu} - \tilde{\tau}$ mixing benchmark scenario:

$$\sigma^{LFV} = \sigma(e^+e^- \to \tilde{\nu}_i\bar{\tilde{\nu}}_i \to LFV - cascade - decays \to \mu^{\pm}\tau^{\mp} + 4\,jets + \not{E}) = 0.14\,fb$$
$$\sigma^{LFC} = \sigma(e^+e^- \to \tilde{\nu}_i\bar{\tilde{\nu}}_i \to LFC - cascade - decays \to \mu^{\pm}\tau^{\mp} + 4\,jets + \not{E}) = 0.0034\,fb$$

⇒ σ^{LFV} can be much larger than σ^{LFC} !

⇒ We can expect good determination of LFV parameters at ILC!

5. Detailed MC study is necessary;

MC analysis of data ⇒ Signal-BG separation for sneutrino (and slepton) production
⇒ measurement of sneutrino (and slepton) observables (including LFV prod. cross sections and LFV decay BR's)
⇒ determination of sneutrino (and slepton) parameters (including LFV parameters) by least-square fitting to these observables!

In any case it is necessary to perform a detailed Monte Carlo study to separate the sneutrino signals from background.
However, such study is beyond the scope of this work.

7. Conclusion

- *We have performed a systematic study of sneutrino production and decays including both fermionic and bosonic decays in the general MSSM with slepton generation mixings.*

- *We have shown that LFV sneutrino decay branching ratios can be quite large due to LFV in slepton sector (i.e. due to slepton generation mixing) in a significant part of the MSSM parameter space despite the recent very strong experimental limits on LFV processes.*

- *This could have an important impact on*
  the search for sneutrinos
  and
  the MSSM parameter determination
  at future colliders, such as LHC, ILC, CLIC and muon collider.