# Lepton Flavor Violation in stau decays at LHC/LC

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# Introduction

o S-leptons mass matrix in the MSSM.

o Sleptons flavor change as the source of FV in the charged lepton sector.

o LFV in neutralino decays at the LHC.

o A suitable phenomenological model: CMSSM+SU(5)+See-Saw

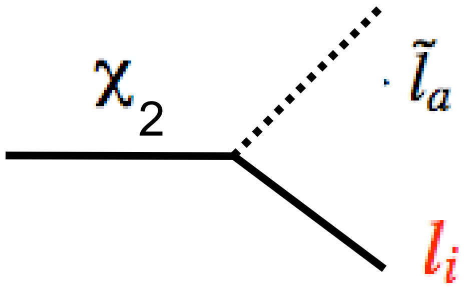
o Flavor mixing in sleptons and LFV.

o PHYTIA simulation for selected points.

o LFV in the LC

# $\chi_2 \rightarrow \chi + \tau^{\pm}\mu^{\mp}$ at LHC

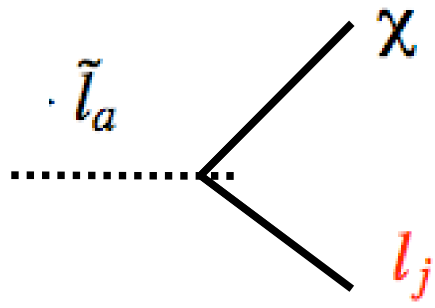
Lepton pairs in neutralino decays:




$\chi_2 \rightarrow \tilde{l}_a \; l_i$

↓

$\chi \; l_j$




In the basis $\tilde{\ell}_i = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R^*, \tilde{\mu}_R^*, \tilde{\tau}_R^*)$, the slepton mass matrix:

$$\mathcal{L}_M = -\frac{1}{2}\tilde{\ell}^\dagger M^2_{\tilde{\ell}}\tilde{\ell}, \qquad M^2_{\tilde{\ell}} = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^2_{RL} & M^2_{RR} \end{pmatrix},$$

$$\begin{aligned} M^2_{LL} &= \frac{1}{2} m_\ell^\dagger m_\ell + M_L^2 - \frac{1}{2}(2m_W^2 - m_Z^2)\cos 2\beta \; I \\ M^2_{RR} &= \frac{1}{2} m_\ell^\dagger m_\ell + M_R^2 - (m_Z^2 - m_W^2)\cos 2\beta \; I \\ M^2_{LR} &= (A^e - \mu \tan\beta) \;\; m_\ell \\ M^2_{RL} &= (M^2_{LR})^\dagger \end{aligned}$$

# Minimal FV: Universal soft terms at GUT(mSUGRA models).

→In a basis such that ***$m_l$*** is diagonal:

$$M^2_{\tilde{\ell}} = \left( \begin{array}{ccc|ccc} m^2_{\tilde{e}_L} & 0 & 0 & \bar{A}_{\tilde{e}} \cdot m_e & 0 & 0 \\ 0 & m^2_{\tilde{\mu}_L} & 0 & 0 & \bar{A}_{\tilde{\mu}} \cdot m_\mu & 0 \\ 0 & 0 & m^2_{\tilde{\tau}_L} & 0 & 0 & \bar{A}_{\tilde{\tau}} \cdot m_\tau \\ \hline \bar{A}_{\tilde{e}} \cdot m_e & 0 & 0 & m^2_{\tilde{e}_R} & 0 & 0 \\ 0 & \bar{A}_{\tilde{\mu}} \cdot m_\mu & 0 & 0 & m^2_{\tilde{\mu}_R} & 0 \\ 0 & 0 & \bar{A}_{\tilde{\tau}} \cdot m_\tau & 0 & 0 & m^2_{\tilde{\tau}_R} \end{array} \right)$$

The 1th and 2th generation sleptons are almost degenerated:

$$m_{\tilde{\tau}_L} < m_{\tilde{e}_L} = m_{\tilde{\mu}_L} \quad ; \quad m_{\tilde{\tau}_R} < m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$$

- The NLSP is mostly $\tilde{\tau}_R$ $\quad m_{\tilde{\tau}_R} < m_{\tilde{\tau}_L}$

Due to the mass degeneration of the 1 and 2th generation one should find a similar number of pairs $\tau^\pm e^\mp$ , $\tau^\pm \mu^\mp$

# LFV

→In a basis such that $m_l$ is diagonal:

$$M_{\tilde{\ell}}^2 = \left(\begin{array}{ccc|ccc} m_{\tilde{e}_L}^2 & 0 & 0 & \bar{A}_{\tilde{e}}\cdot m_e & 0 & 0 \\ 0 & m_{\tilde{\mu}_L}^2 & M_{LL}^2 & 0 & \bar{A}_{\tilde{\mu}}\cdot m_\mu & 0 \\ 0 & M_{LL}^2 & m_{\tilde{\tau}_L}^2 & 0 & 0 & \bar{A}_{\tilde{\tau}}\cdot m_\tau \\ \hline \bar{A}_{\tilde{e}}\cdot m_e & 0 & 0 & m_{\tilde{e}_R}^2 & 0 & 0 \\ 0 & \bar{A}_{\tilde{\mu}}\cdot m_\mu & 0 & 0 & m_{\tilde{\mu}_R}^2 & M_{RR}^2 \\ 0 & 0 & \bar{A}_{\tilde{\tau}}\cdot m_\tau & 0 & M_{RR}^2 & m_{\tilde{\tau}_R}^2 \end{array}\right)$$

Flavor mixing entries are defined as

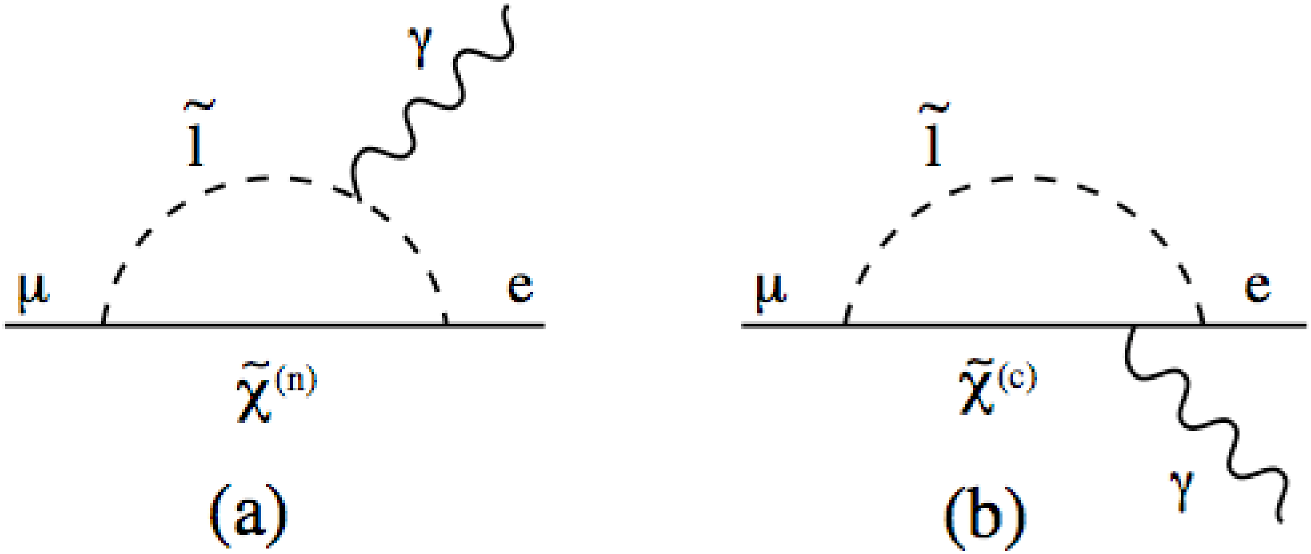
$$\delta_{XX}^{ij} = (M_{XX}^2)^{ij}/(M_{XX}^2)^{ii} \quad (X = L, R).$$

Due to LFV there are an excess of $\tau^{\pm}\mu^{\mp}$ over $\tau^{\pm}e^{\mp}$ pairs.

Hinchliffe+Paige, PRD63(2001)

# Charged Lepton Flavor Violation

In SUSY flavor mixing lepton-slepton vertices can induce LFV diagrams:




Lepton-slepton flavor mixing is very constrained by the experimental limits:

$$
\begin{aligned}
BR(\mu \to e\gamma) &< 1.9 \cdot 10^{-11} \\
BR(\tau \to \mu\gamma) &< 4.5 \cdot 10^{-8} \\
BR(\tau \to e\gamma) &< 1.1 \cdot 10^{-7}
\end{aligned}
$$

# $\chi_2 \to \chi + \tau^{\pm} + \mu^{\mp}$ at LHC.

- On-shell slepton production:

$$BR(\chi_2 \to \chi\tau^{\pm}\mu^{\mp}) = \sum_{i=1}^{3} BR(\chi_2 \to \tilde{l}_i\mu)BR(\tilde{l}_i \to \tau\chi) + BR(\chi_2 \to \tilde{l}_i\tau)BR(\tilde{l}_i \to \mu\chi)$$

Bartl et al,
hep-ph/0510074

- the signal in the $\tau$ channel to be optimal is definded by the following:

B

(i) $m_{\chi_2^0} > m_{\tilde{\tau}} > m_{\chi}^0$ (on-shell condition)

(ii) $m_{\tilde{\tau}} >> m_{\chi}^0$ (hadronised $\tau$s in the final state)

(iii) Moderate values of $m_{\chi}^0$ (phase space and luminosity considerations).

We use PYTHIA to simulate the hadronic decays of τ s produced in the dilepton decay . In the study of the flavor-violating dilepton signal (τ ± μ-+), the second lepton is tagged as a muon with a probability equal to the branching ratio assumed for flavor-violating decays.

In order to have a visible signal we need:

$$\frac{\Gamma(\chi_2 \to \chi + \tau^{\pm}\mu^{\mp})}{\Gamma(\chi_2 \to \chi + \tau^{\pm}\tau^{\mp})} \sim 0.1$$

# SU(5) RGE effects

The running of the soft terms from a higher scale ($M_X$) to $M_{GUT}$ introduce non universalities on the soft terms :

- $M_x \to M_{GUT}$

$$W_{SU(5)} = \frac{1}{4} f_u^{ij}\, 10_i\, 10_j\, H + \sqrt{2} f_d^{ij}\, 10_i\, \overline{5}_j\, \overline{H} + f_\nu^{ij}\, 1_i\, \overline{5}_j\, H$$

$$f_u^{ij} = f_u^{\delta},$$

$$f_d^{ij} = V_{CKM}^{*} \lambda_d^{\delta} V_{KM}^{\dagger}$$

The soft terms:

$$m_{10}\, \widetilde{10} * \widetilde{10} + m_5\, \widetilde{5} * \widetilde{5} + \cdots$$

$$\widetilde{\ell}_R \text{ in } 10's \to m^2_{\widetilde{\ell}_R} = V^{\dagger}_{\rm CKM} m^2_{10} V_{\rm CKM}$$

# See-saw Neutrinos and SUSY

Even if we start with universal soft terms at GUT, FV entries can be generated:

$$M_{\rm GUT}: m_{\tilde{\ell},\tilde{\nu}} \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \text{RGEs} \longrightarrow \begin{pmatrix} 1 & \star & \star \\ \star & 1 & \star \\ \star & \star & 1 \end{pmatrix}$$

- RGEs for the charged-lepton mass matrix

$$t\frac{d}{dt}\left(m^2_{\tilde{\ell}}\right)^j_i = \frac{1}{16\pi^2}\left\{\left(m^2_{\tilde{\ell}}\lambda^\dagger_\ell\lambda_\ell\right)^j_i + \left(m^2_{\tilde{\nu}}\lambda^\dagger_\nu\lambda_\nu\right)^j_i + \cdots\right\}$$

The corrections in the basis where $(\lambda^\dagger_\ell\lambda_\ell)^j_i$ is diagonal, are:

$$\delta m^2_{\tilde{\ell}} \propto \frac{1}{16\pi}\ln\frac{M_{\rm GUT}}{M_N}\lambda^\dagger_\nu\lambda_\nu m^2_{SUSY}$$

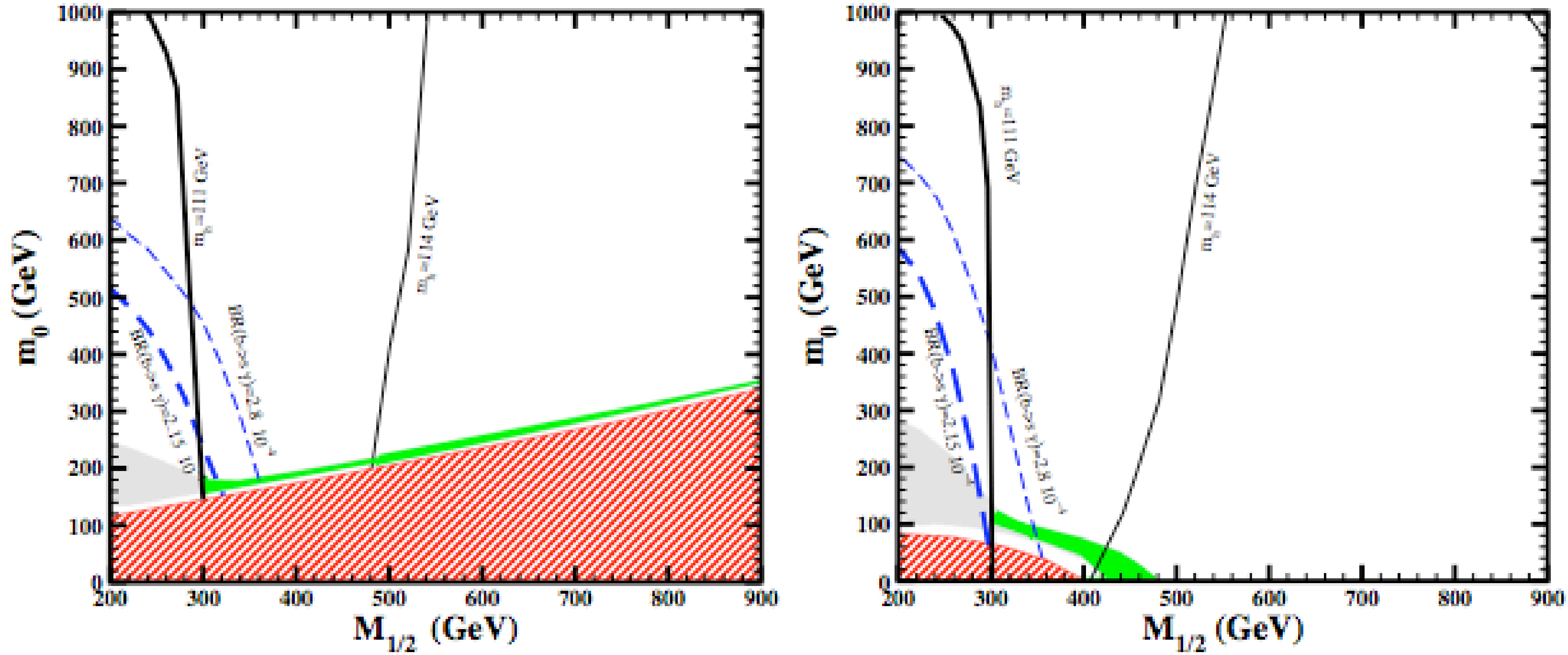
- $M_{GUT} \to M_R$

$$
\begin{aligned}
W_{\mathrm{MSSM}+\nu_R} &= Q^T\, f_u^\delta\, U\, H_2 + Q^T \left(V_{CKM}^\dagger f_d^\delta\right) D\, H_1 \\
&+ L^T \left(V_{KM}^* f_\ell^\delta\right) E\, H_1 + L^T f_\nu^\delta\, N\, H_2
\end{aligned}
$$

Remember that the $V_{KM} = V_\nu^+ \cdot V_l$ where $V_\nu^+ \cdot f_\nu^+ f_\nu \cdot V_\nu = (f_\nu^\delta)^2$ and $V_l^+ \cdot f_l^+ f_l \cdot V_l = (f_l^\delta)^2$. (Does not involve the RH neutrinos like the $V_{NMS}$). At scale $M_R$, the diagonal charged lepton Yukawa implies:

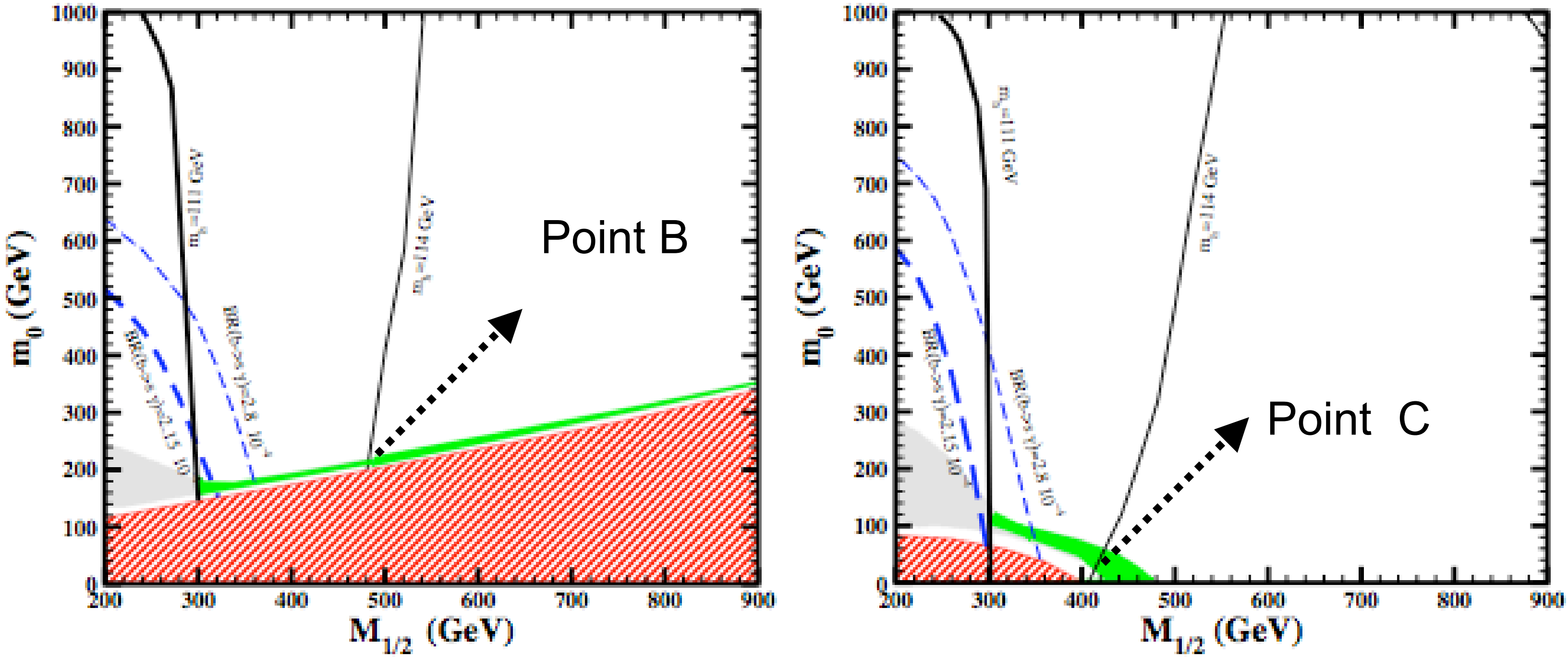
$$
L^* \left(m_l^2\right)^{diag} L \to L^* \left[V_{KM}^\dagger \cdot \left(m_l^2\right)^{diag} \cdot V_{KM}\right] L
$$

# Cosmologically-favored areas, selection of points




*In the left panel we assume universality at* $M_X = M_{GUT}$, *whereas in the right panel we assume universality at* $M_X = 2 \cdot 10^{17}$ *GeV. The red areas are excluded because* $m_\chi > m_{\tilde{\tau}}$. *We also display the contours for* $m_h = 111, 114$ *GeV (black solid and thin solid) and* $BR(b \to s\gamma) \cdot 10^4 < 2.15, 2.85$ *(blue dashed and thin dashed).*

# Cosmologically-favored areas, selection of points

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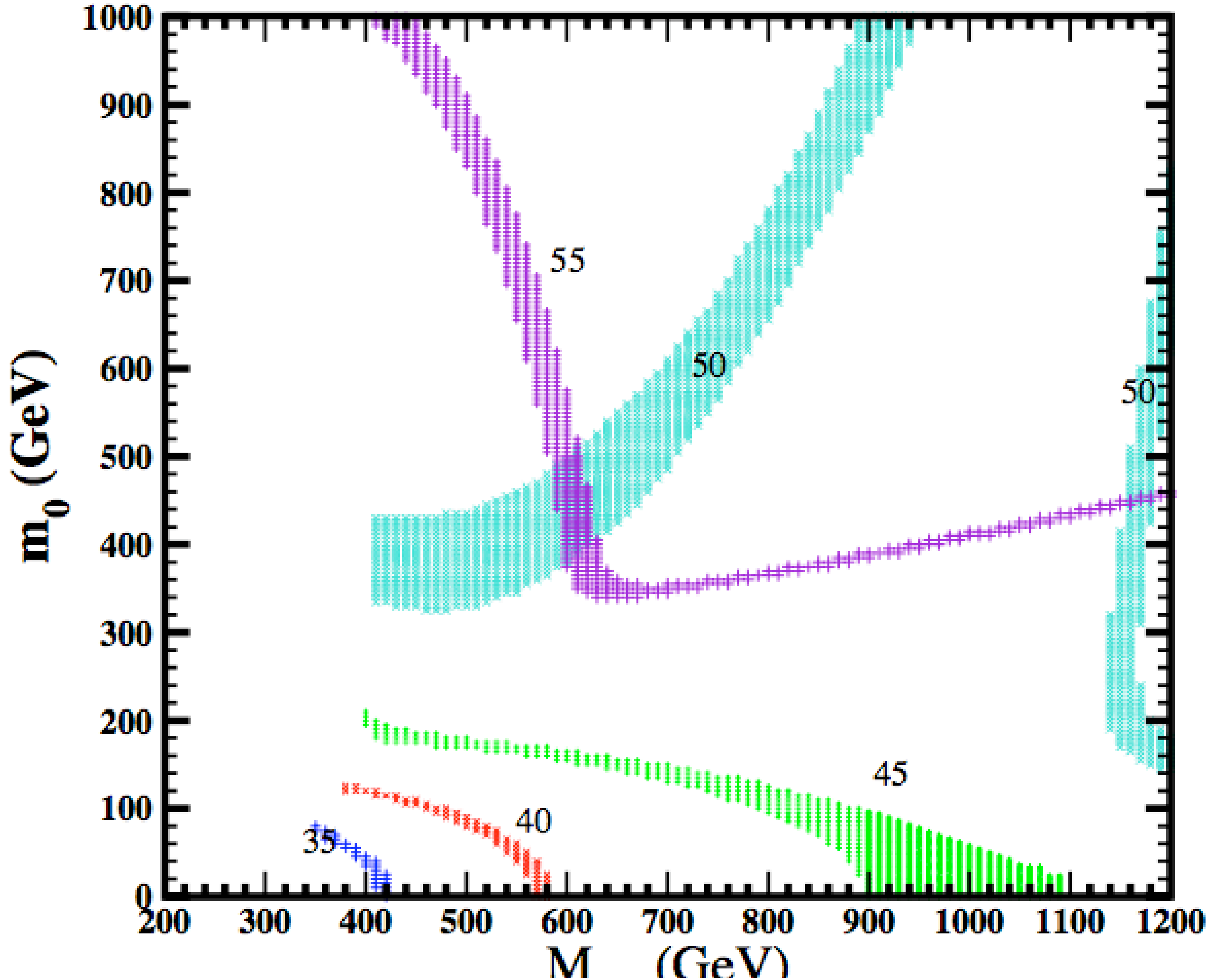
A0=0, mb(MZ)=2.92 GeV



# Selection of Points for the Analysis

| *Point* | *Modeltype* | $m_0$ | $M_{1/2}$ | $\tan\beta$ | $A_0$ | $N_{events}$ | $\sigma_{int}$ | $L_{int}$ |
|---|---|---|---|---|---|---|---|---|
| A | CMSSM | 100 | 300 | 10 | 300 | 757K | 25.3 pb | 30 $fb^{-1}$ |
| B | SU(5) | 40 | 450 | 35 | 40 | 730 K | 2.44 pb | 300 $fb^{-1}$ |
| C | CMSSM | 220 | 500 | 35 | 220 | 536 K | 1.79 pb | 300 $fb^{-1}$ |

| *Point* | $M_{\tilde{g}}$ | $M_{\tilde{u}_L}$ | $M_{\tilde{d}_L}$ | $M_{\tilde{\chi}_2^0}$ | $M_{\tilde{\tau}_1}$ | $M_{\tilde{\chi}_1^0}$ | $M_{\tilde{l}_R}$ | $M_{\tilde{l}_L}$ | $M_h$ |
|---|---|---|---|---|---|---|---|---|---|
| A | 720 | 664 | 669 | 216 | 150 | 118 | 155 | 232 | 110 |
| B | 1095 | 1025 | 1024 | 366 | 207 | 194 | 286 | 371 | 117 |
| C | 1154 | 1074 | 1078 | 388 | 219 | 206 | 290 | 405 | 116 |

*Reference points and relevant sparticle masses (in GeV)*

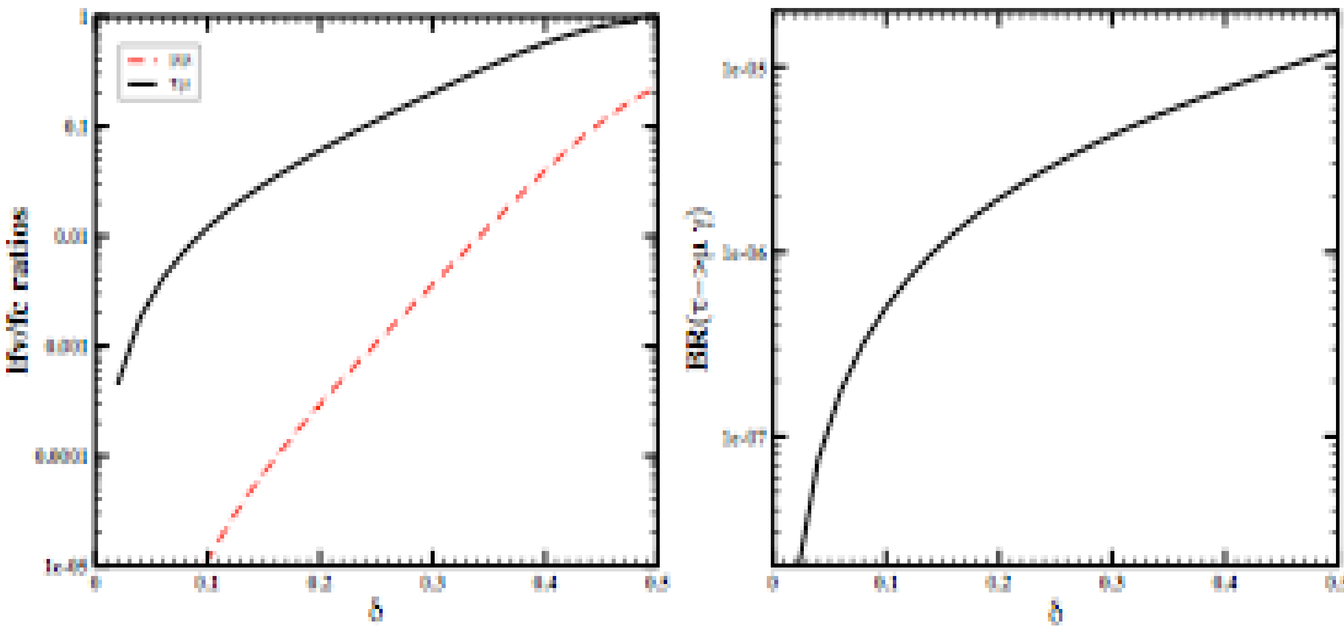
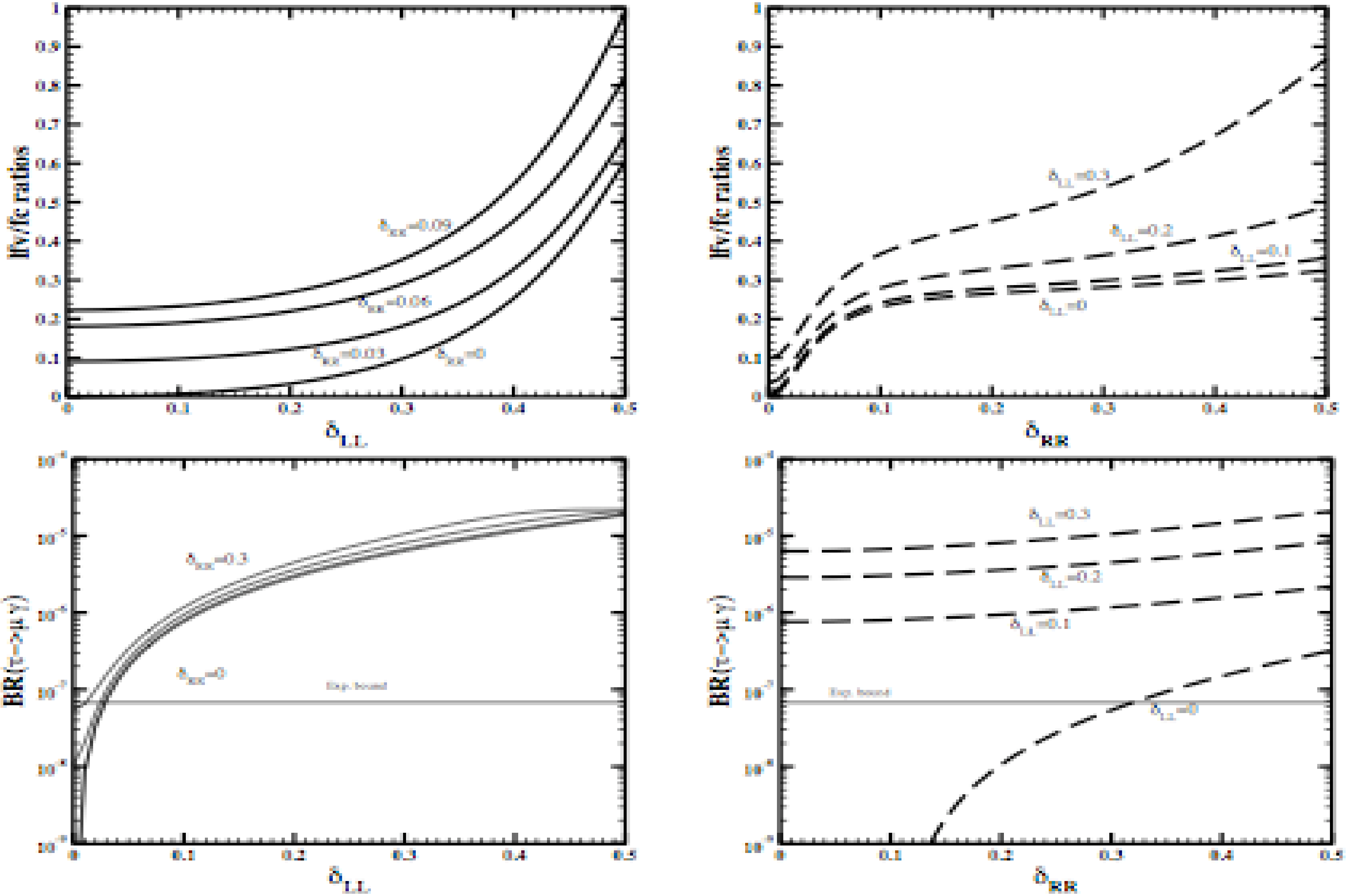
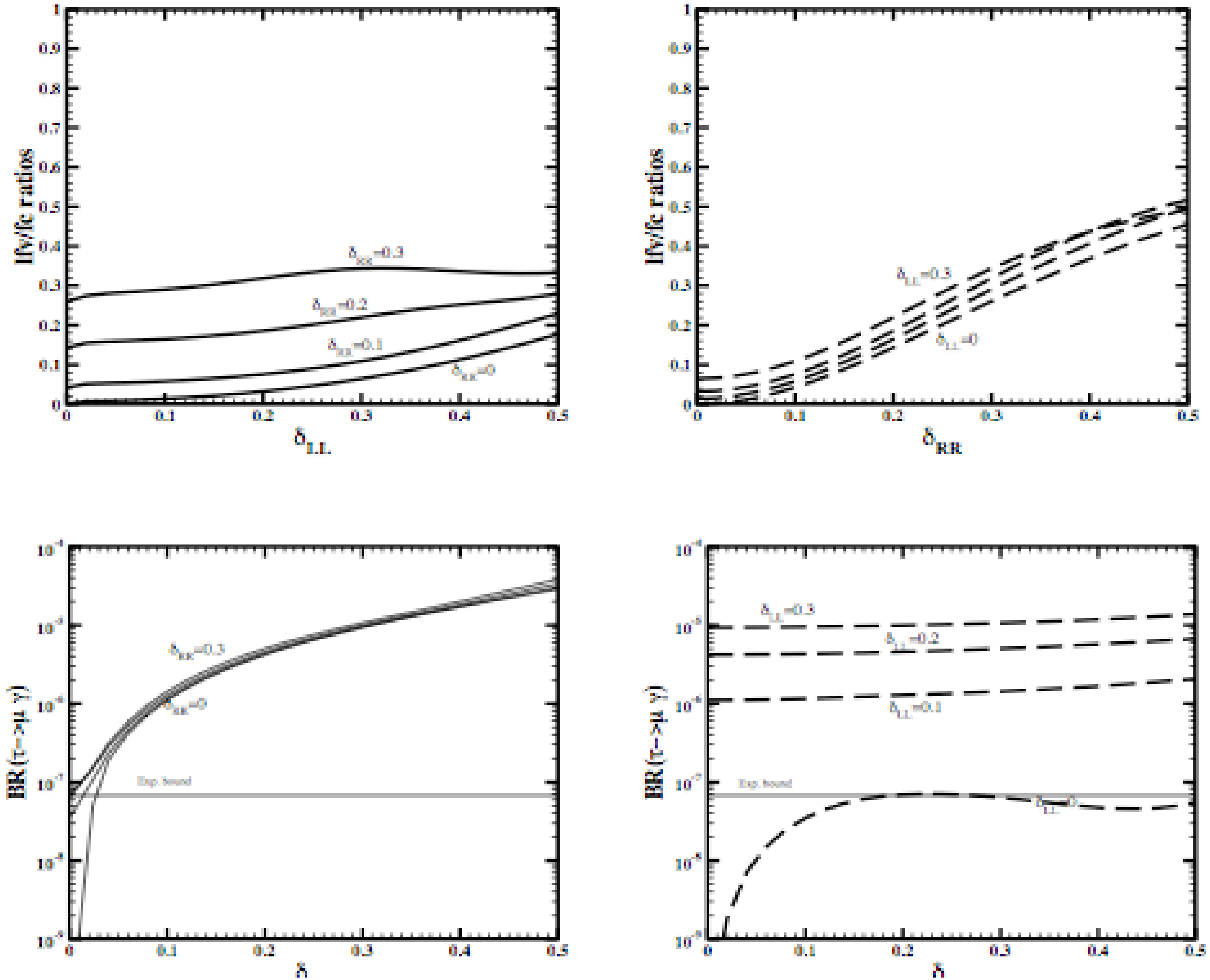


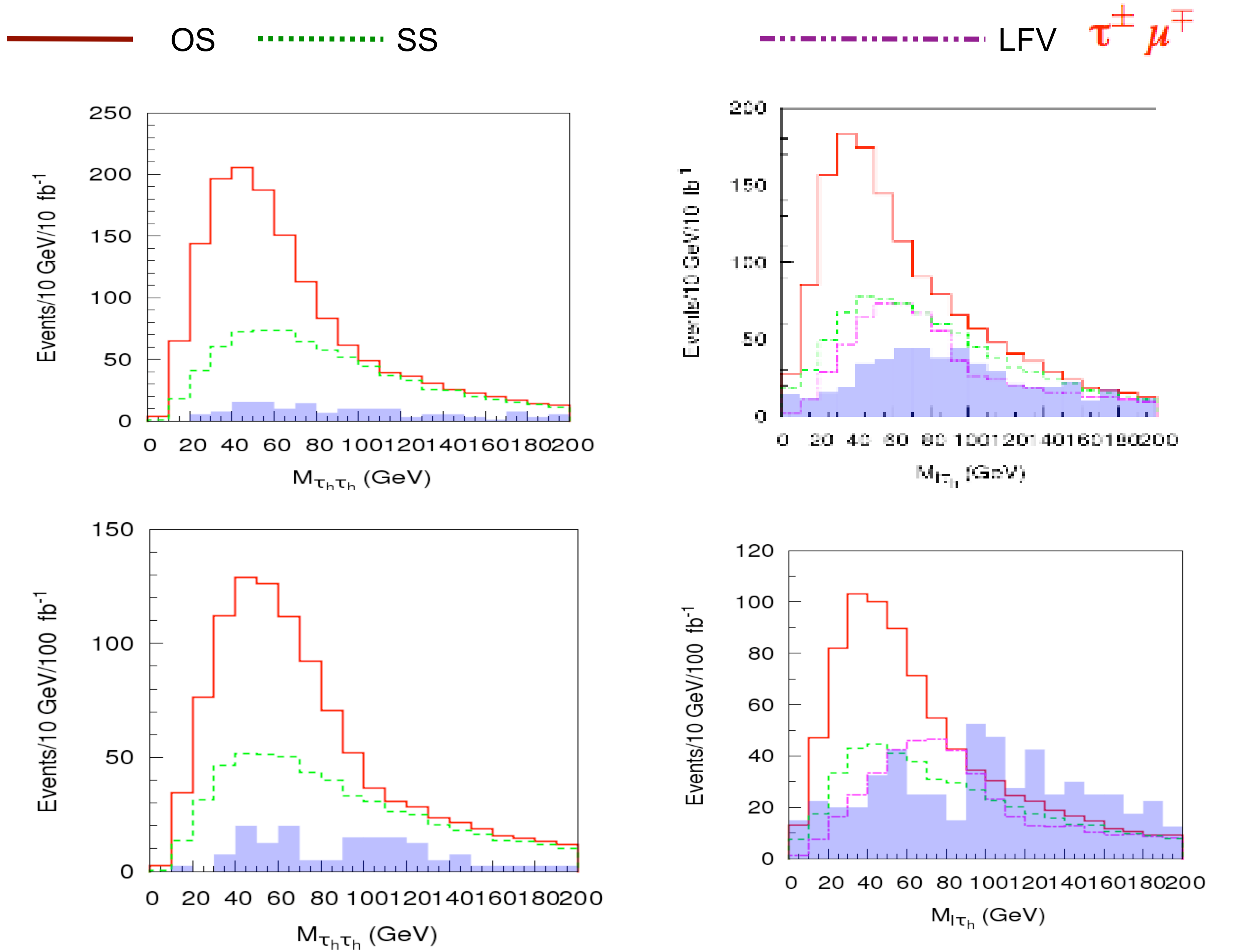
**Figure 1.** In the left panel, flavor-conserving and -violating dilepton branching ratios are calculated for point A, for comparison with figure 1 of [9]. The corresponding expectations for $\tau \to \mu\gamma$ decay are shown in the right panel as a function of $\delta$.

$$\frac{\Gamma(\chi_2 \to \chi + \tau^{\pm}\mu^{\mp})}{\Gamma(\chi_2 \to \chi + \tau^{\pm}\tau^{\mp})}$$ , $\tau \to \mu\gamma$ vs $\delta_{LL}$ and $\delta_{RR}$



# As previous for points B and C





OS
SS
LFV
$\tau^{\pm}\mu^{\mp}$
Events/10 GeV/10 fb$^{-1}$
$M_{\tau_h\tau_h}$ (GeV)
$M_{l\tau_h}$ (GeV)
Events/10 GeV/100 fb$^{-1}$
$M_{\tau_h\tau_h}$ (GeV)
$M_{l\tau_h}$ (GeV)

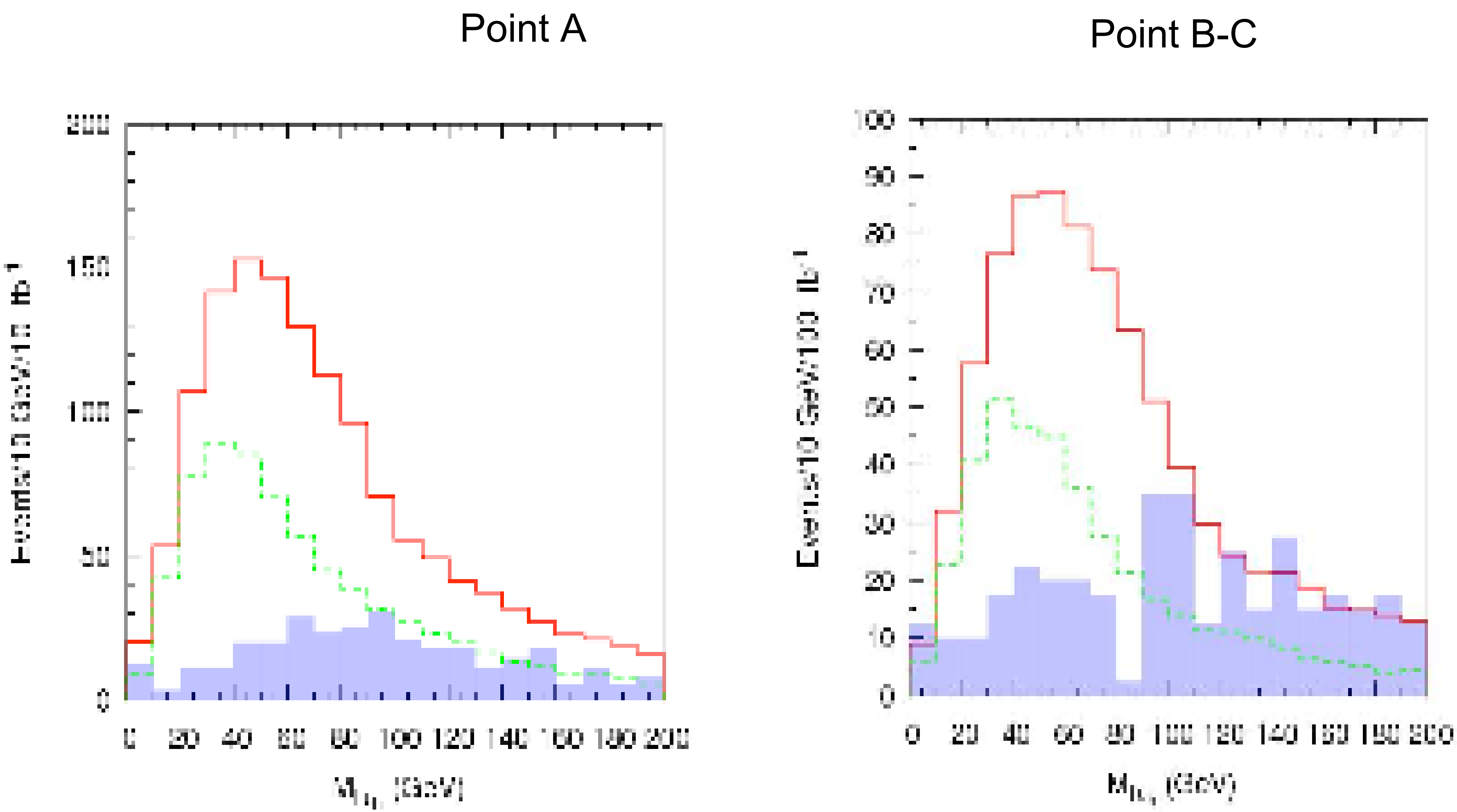
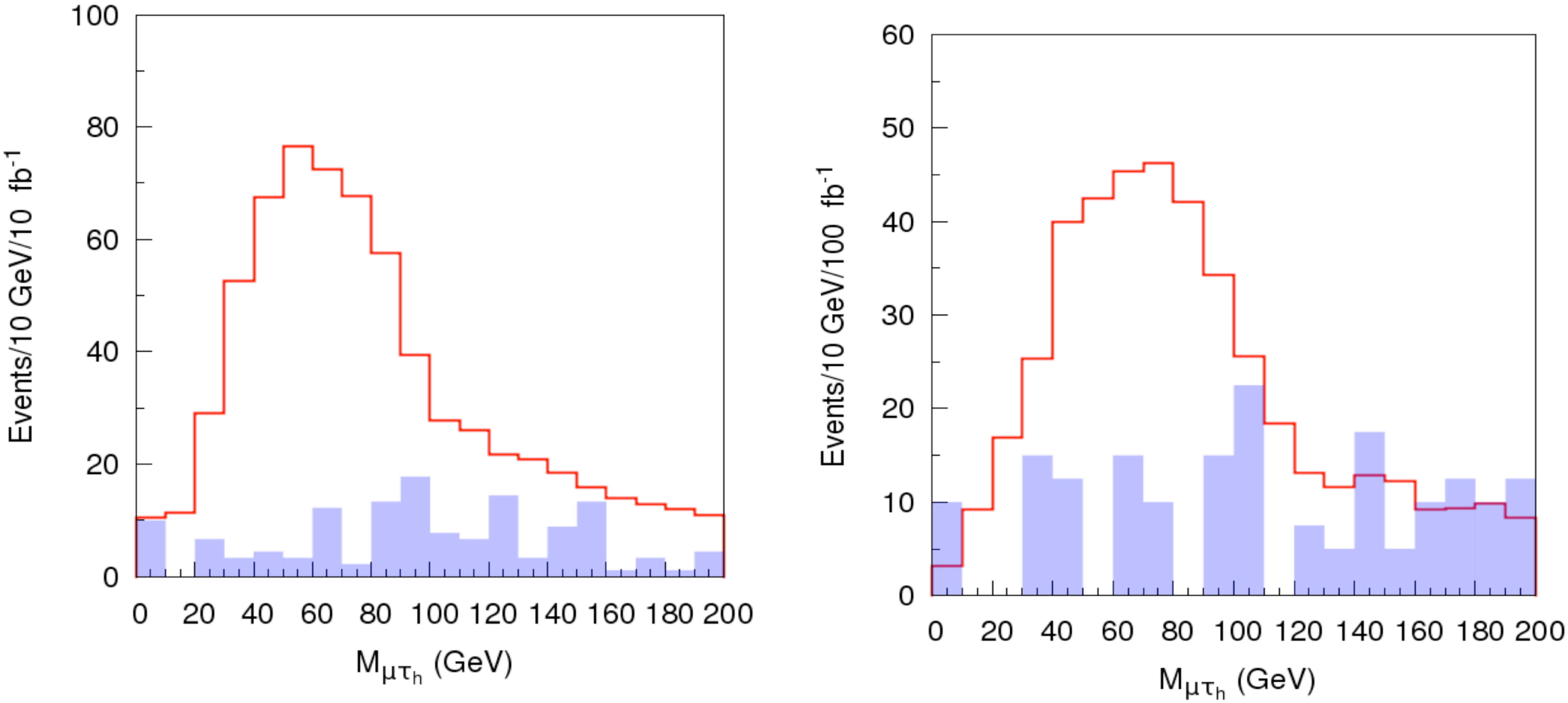


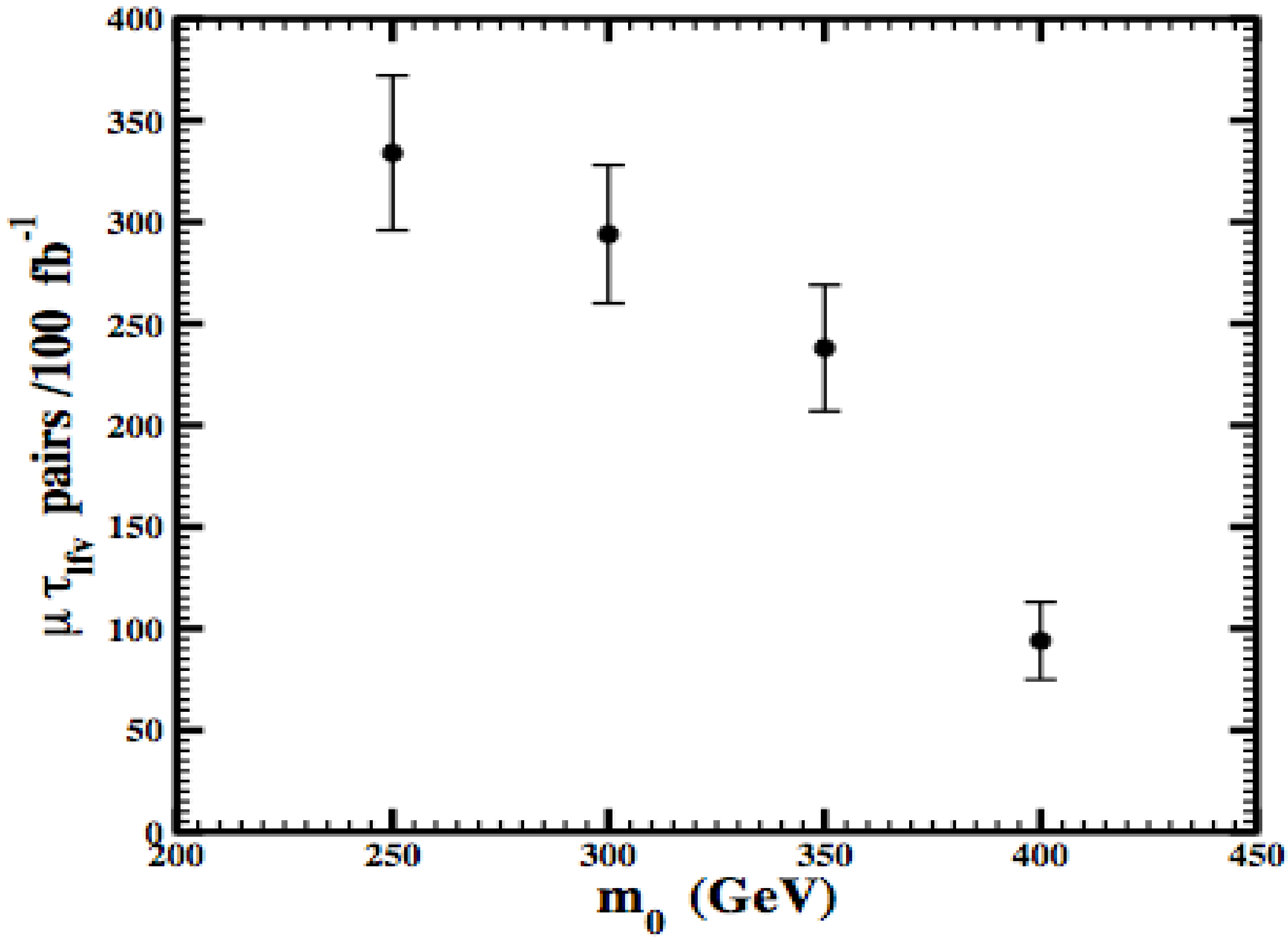

Figure 8. Left: comparisons between the visible mass distributions for $\tau_h\mu$ (red solid lines), $\tau_h e$ (green dashed lines) and Standard Model $\tau_h\mu$ pairs (shaded). The LFV $\mu\tau_h$ pairs have been added to the $\mu\tau_h$ distribution. Right: comparison between the visible mass distributions for LFV

The observable numbers, $N^{lfv}_{\mu\tau_h}$, of $\mu^{\mp}\tau_h^{\pm}$ LFV pairs are obtained by summing the counts in the subtracted $\mu^{\mp}\tau_h^{\pm} - e^{\mp}\tau_h^{\pm}$ distributions in the interval of $M_{l\tau}$ masses between 30 and 110 GeV. With a estimate efficiency of 70 % for the jet-tau matching,

$$\begin{aligned} \text{Point A}: N^{lfv}_{\mu\tau_h} &= 355 \pm 34 \ (10\ \sigma) \\ \text{Point B}: N^{lfv}_{\mu\tau_h} &= 236 \pm 27 \ (9\ \sigma) \end{aligned} \quad (1)$$



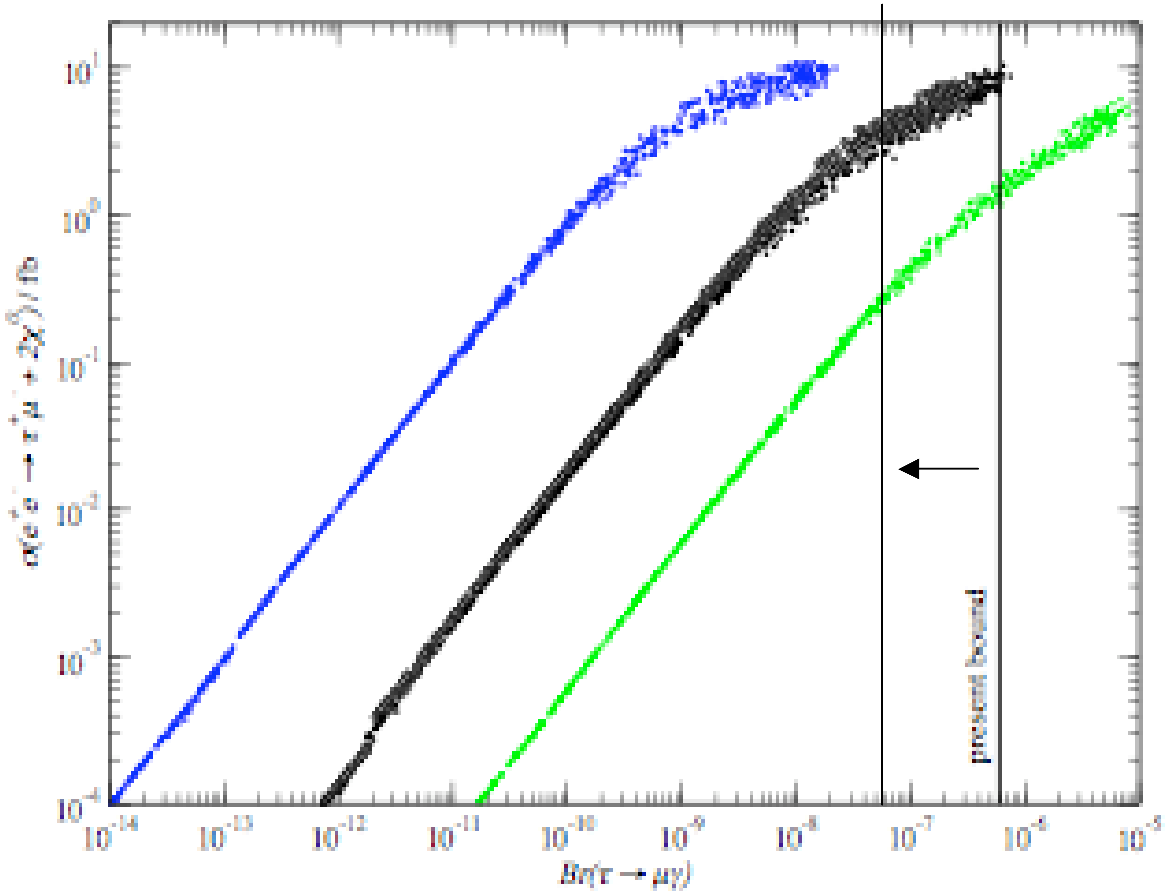
## Results for Varying $m_0$ at Fixed $M_{1/2}$



# LFV at LC

LFV signals from channels like:

$$
\begin{aligned}
e^+e^- &\rightarrow \tilde{\ell}_i^- \tilde{\ell}_j^+ \rightarrow \tau^\pm \mu^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0 \\
e^+e^- &\rightarrow \tilde{\nu}_i \tilde{\nu}_j^c \rightarrow \tau^\pm \mu^\mp \tilde{\chi}_1^+ \tilde{\chi}_1^- \\
e^+e^- &\rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp \rightarrow \tau^\pm \mu^\mp \tilde{\chi}_1^+ \tilde{\chi}_1^- \\
e^+e^- &\rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \tau^\pm \mu^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0
\end{aligned}
$$




Deppisch *et al, Hep-ph/0401243*

# CONCLUSIONS

The observation of LFV in neutralino decays at the LHC can be possible if

$$\Gamma(\chi_2 \to \chi_1 \tau^{\pm} \mu^{\mp}) \,/ \Gamma(\chi_2 \to \chi_1 \tau^{\pm} \tau^{\mp}) \sim 0.1.$$

The strong bounds on radiative τ-decays, as well and cosmological and phenomenological CMSSM and the minimal GUT's with *see-saw* neutrinos are not promising frameworks for obser ving LFV spar ticle decays.

Larger ratios can be found in a non-minimal models, where *RR* slepton mixing may be substantial, enabling the LFV signal to be distinguished clearly from the background.